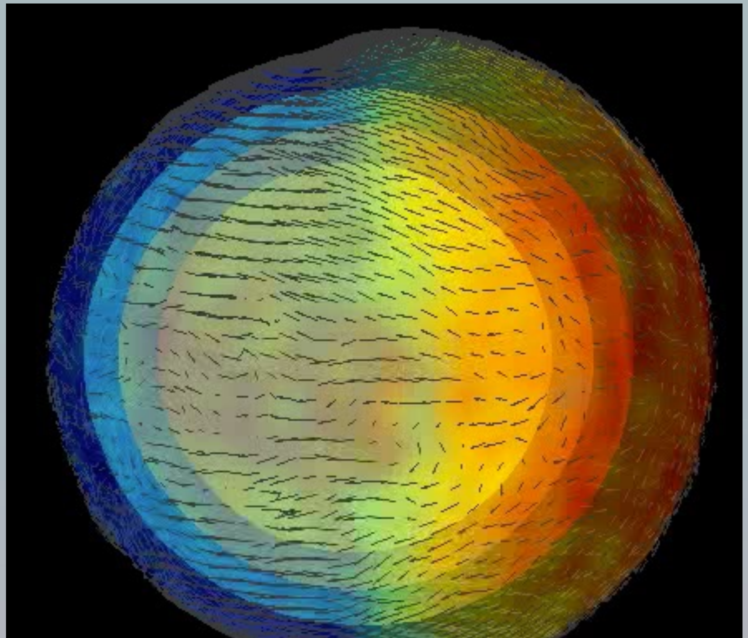
Mapping the 3D Structure of Exoplanet Atmospheres using Transit Spectroscopy



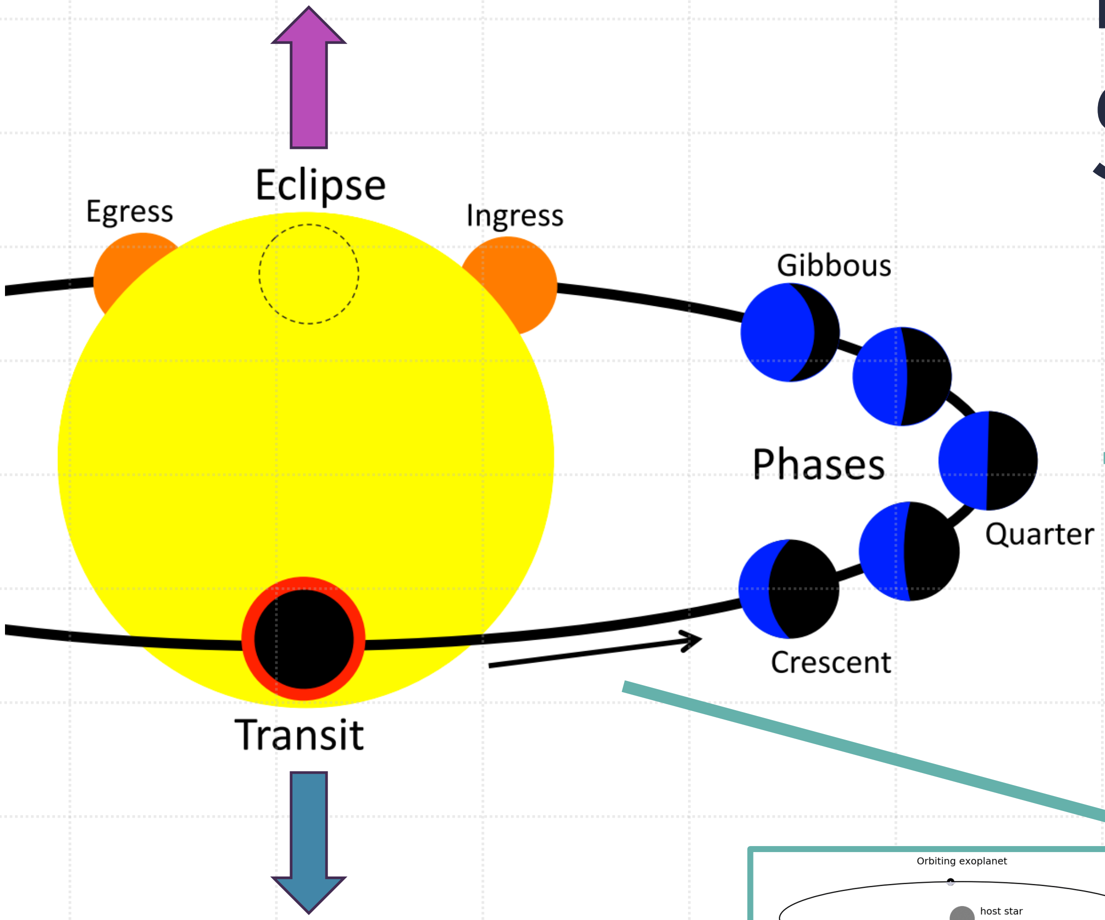
Credit: D. Spiegel
Rauscher & Menou (2010)

Emily Rauscher (she/her)

University of Michigan

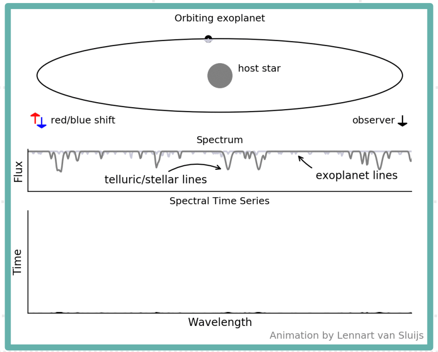
Methods of Transit Spectroscopy

Eclipse mapping
3D structure of dayside



Orbital (rotational) phase curves
2D structure in longitude and pressure

Transit mapping
3D structure of terminator



Phase-dependent high-resolution spectroscopy
2D structure in longitude and pressure

The geometries are different, but both techniques share the same basics

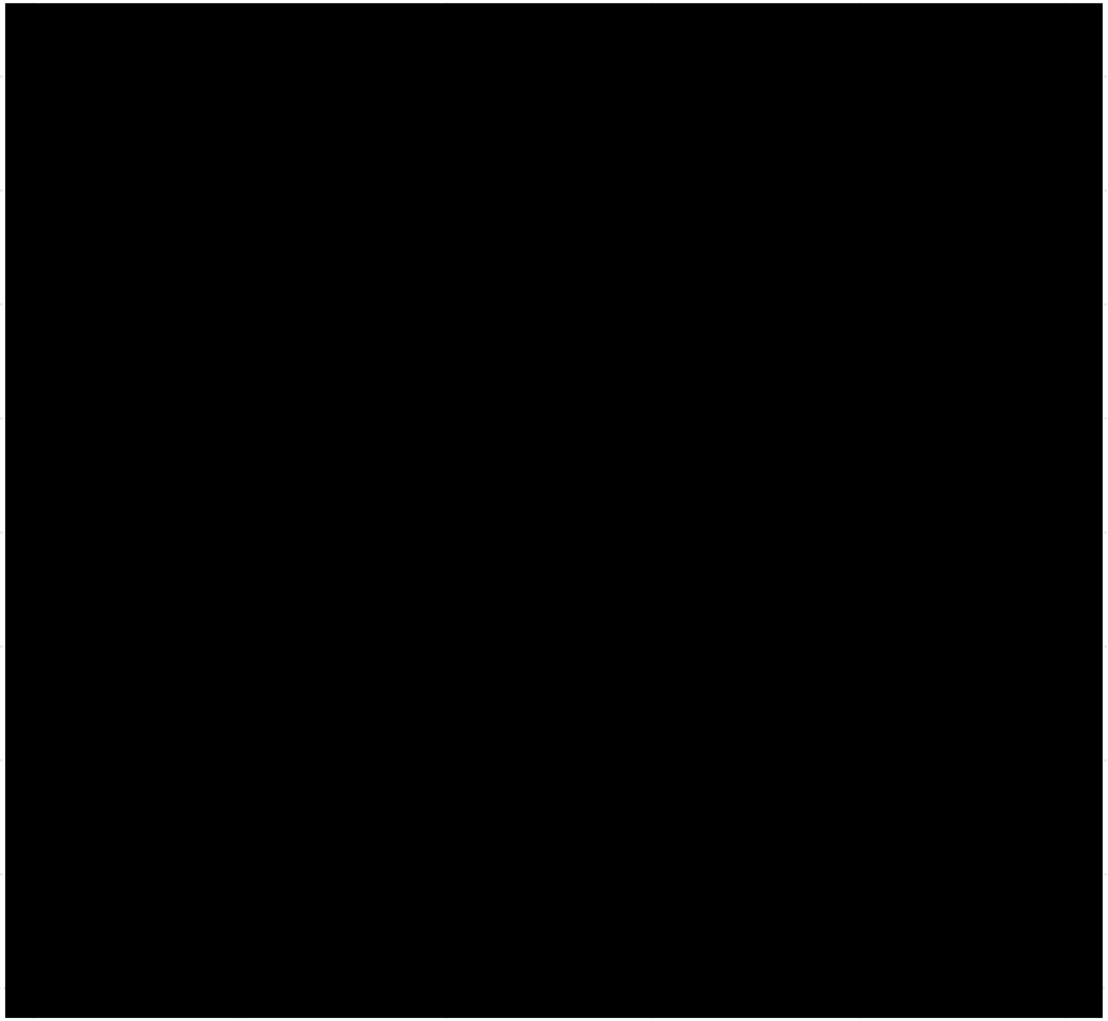
Eclipse mapping → ← ***Transit mapping***

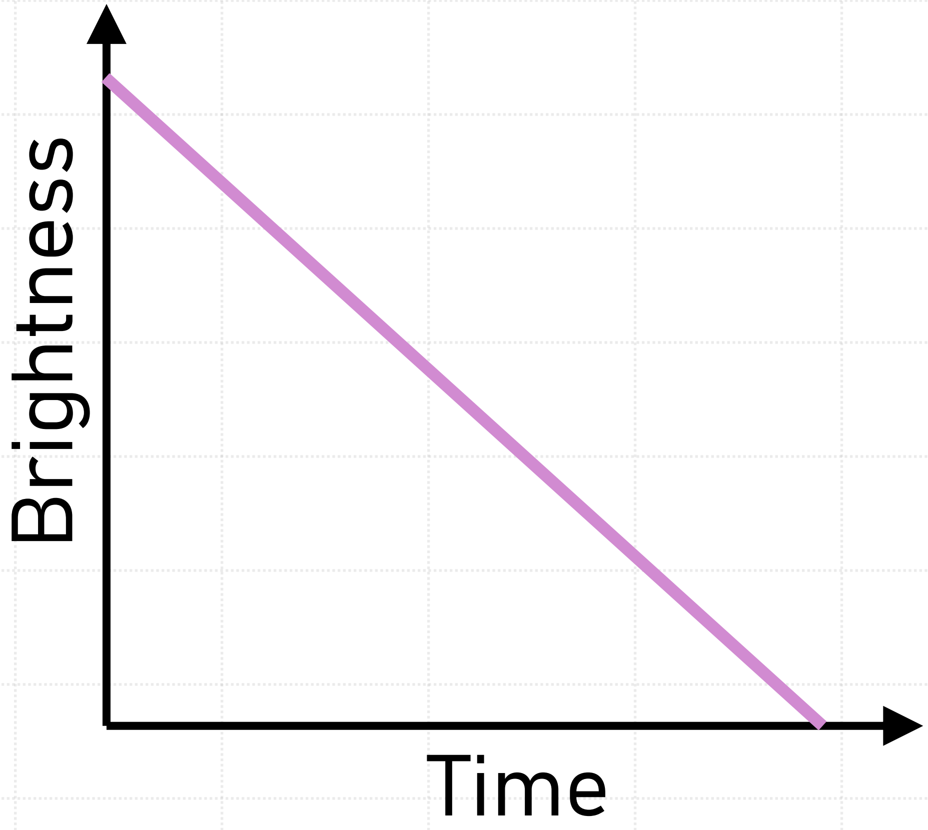
- How to access 3D info:
  - Latitude and longitude come from the shape of the light curve
  - Depth into the atmosphere comes from spectral differences
- Methods to extract 3D info:
  - Model-independent
  - Model-informed

Basic concepts of 3D mapping

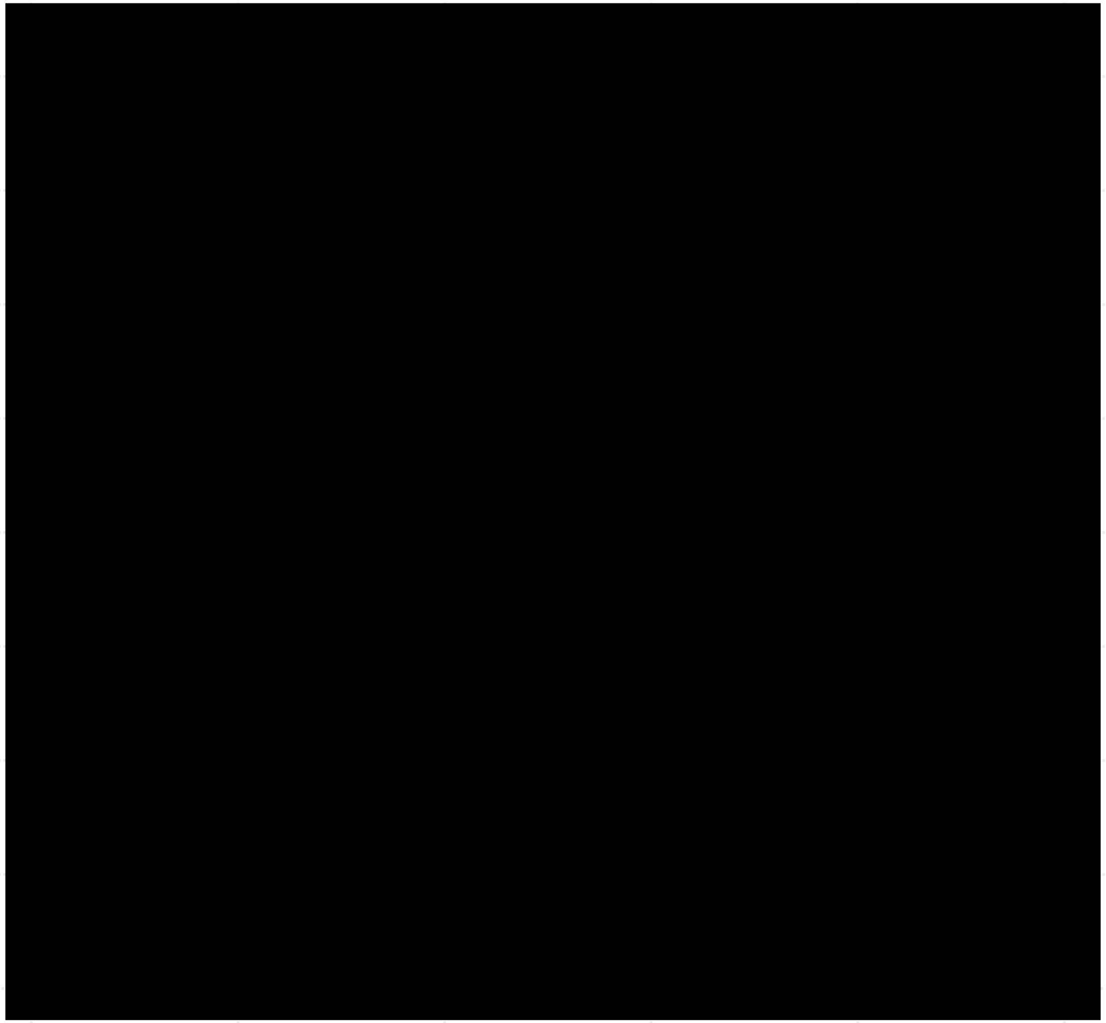
1. The 3D info comes from the shape and wavelength-dependence of the light curve
2. Extracting that info requires applying assumptions

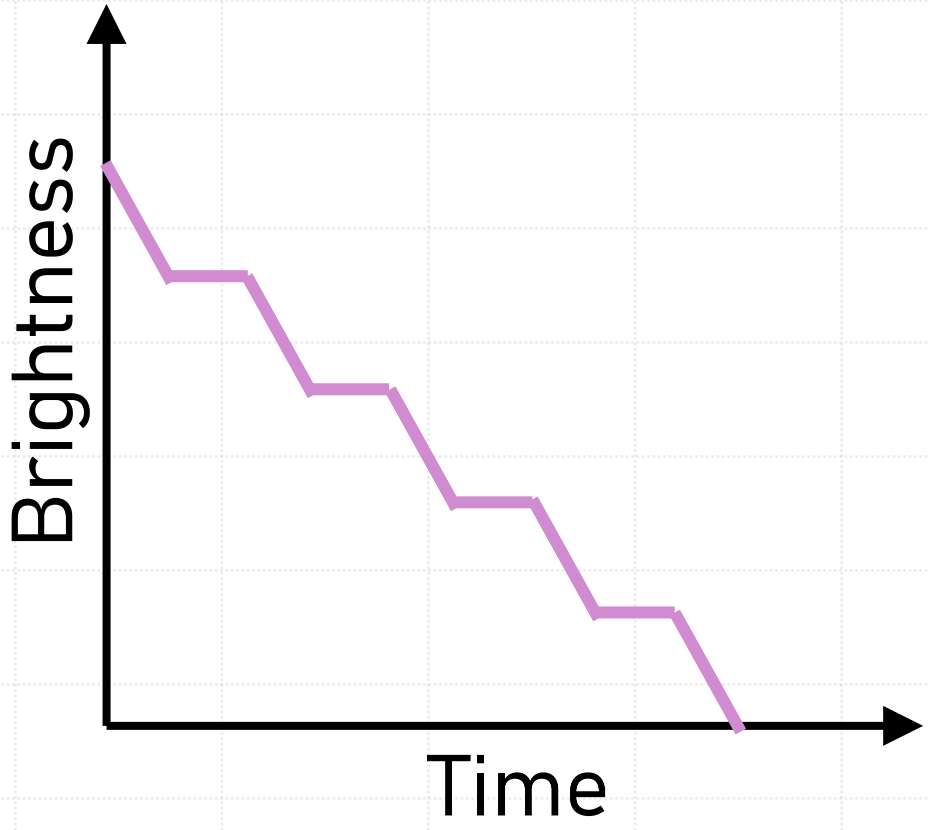
Eclipse mapping: a cartoon example





Eclipse mapping: a cartoon example





Eclipse mappi

- How to access 3D info:
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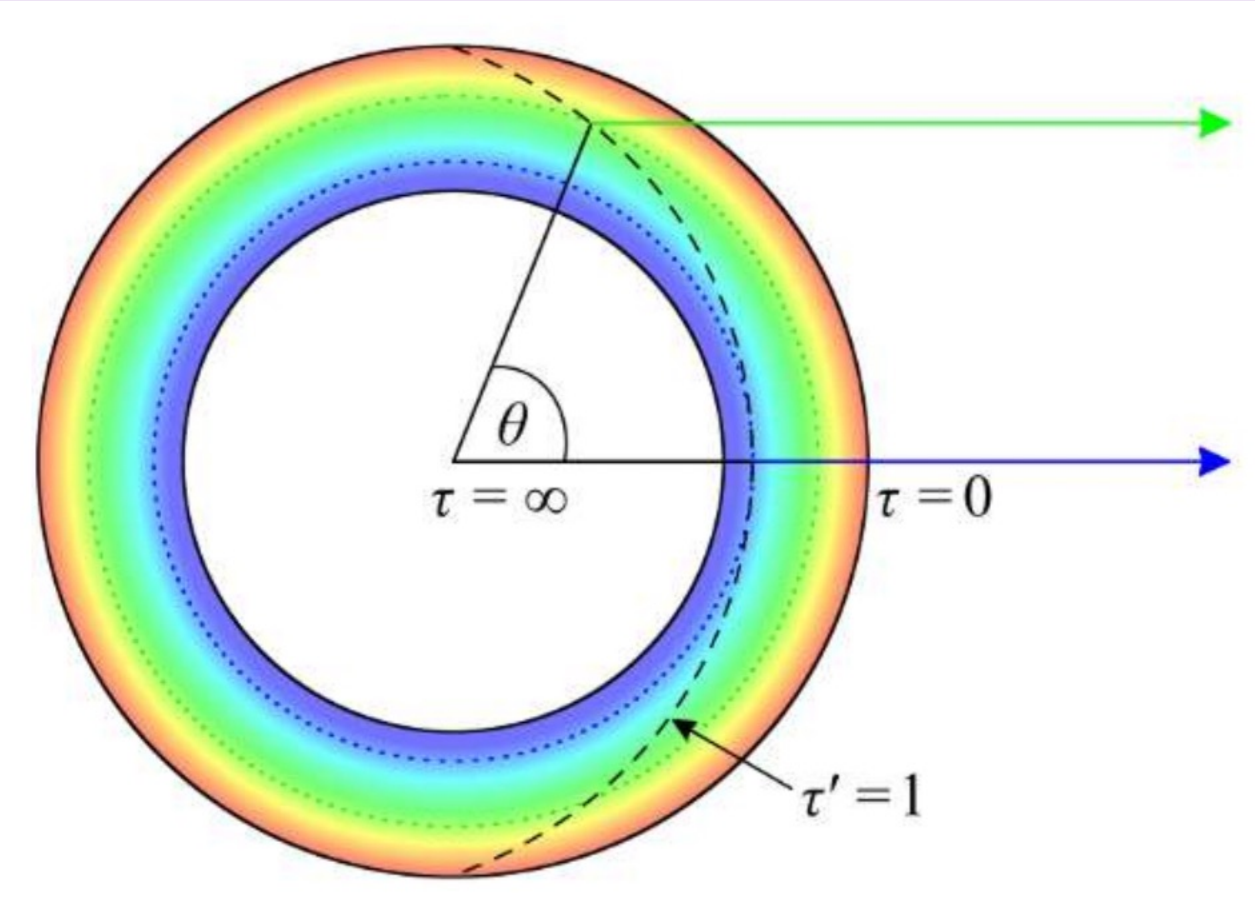


Eclipse mapping: a more complex example

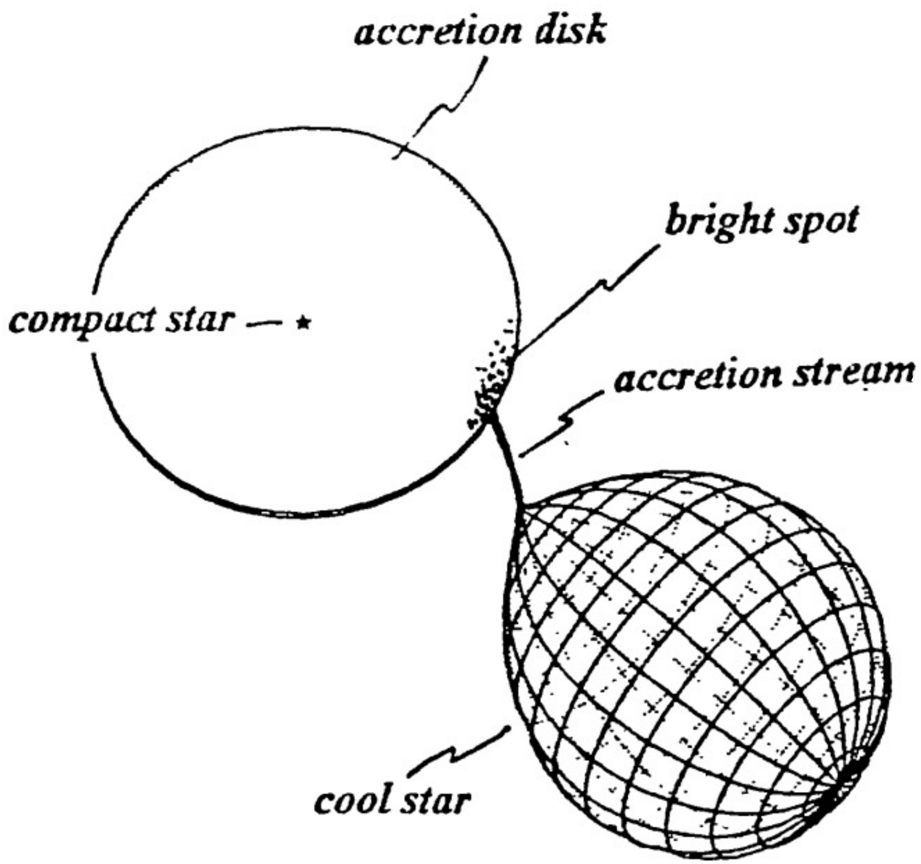
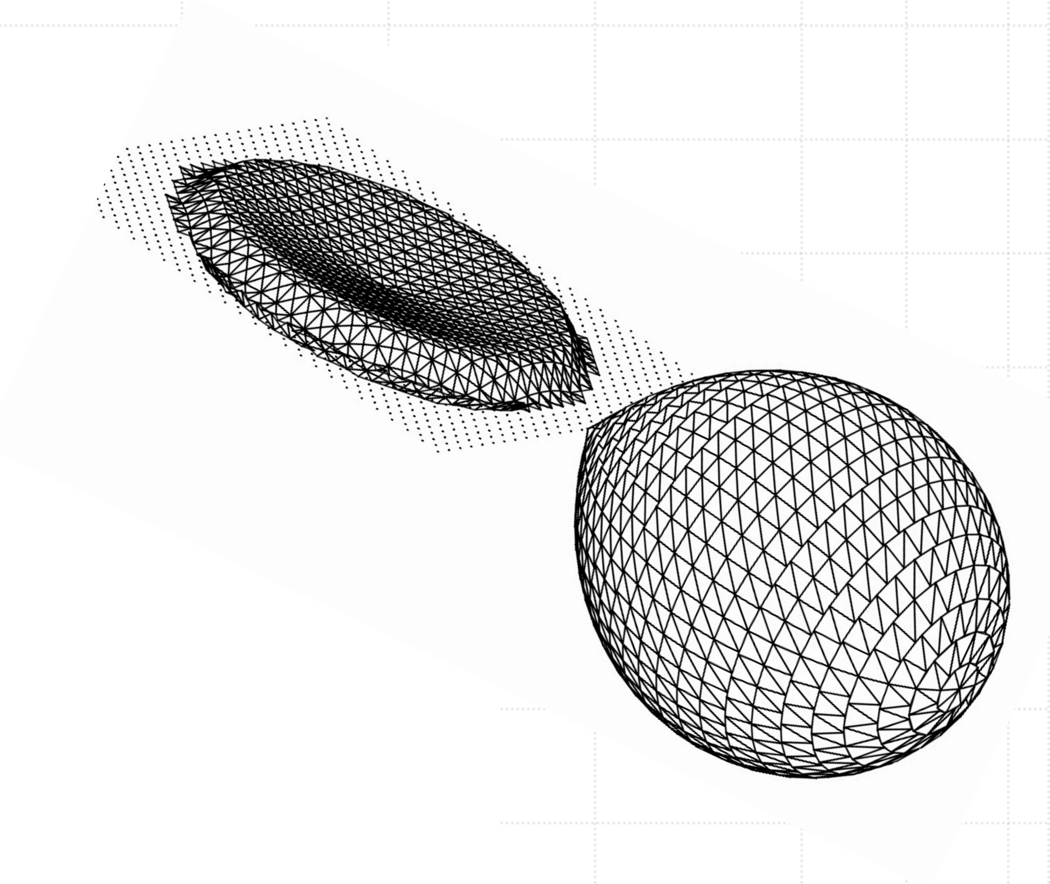
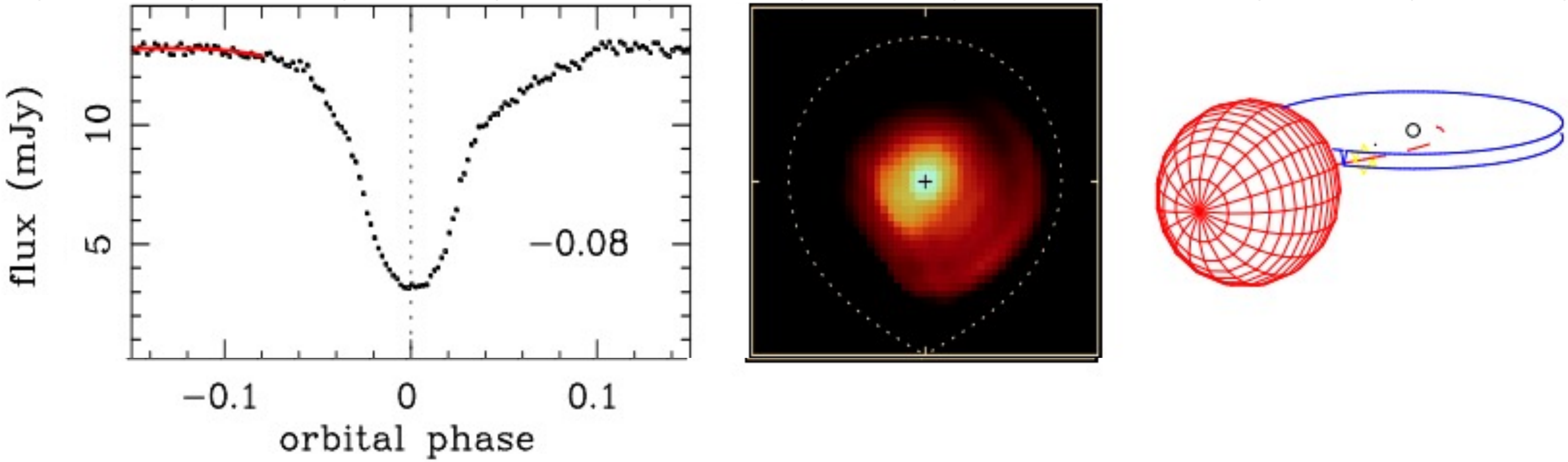


Figure 1. Representation of a cataclysmic variable star with the Roche-lobe filling secondary star, the accretion disk, and the compact white dwarf indicated.



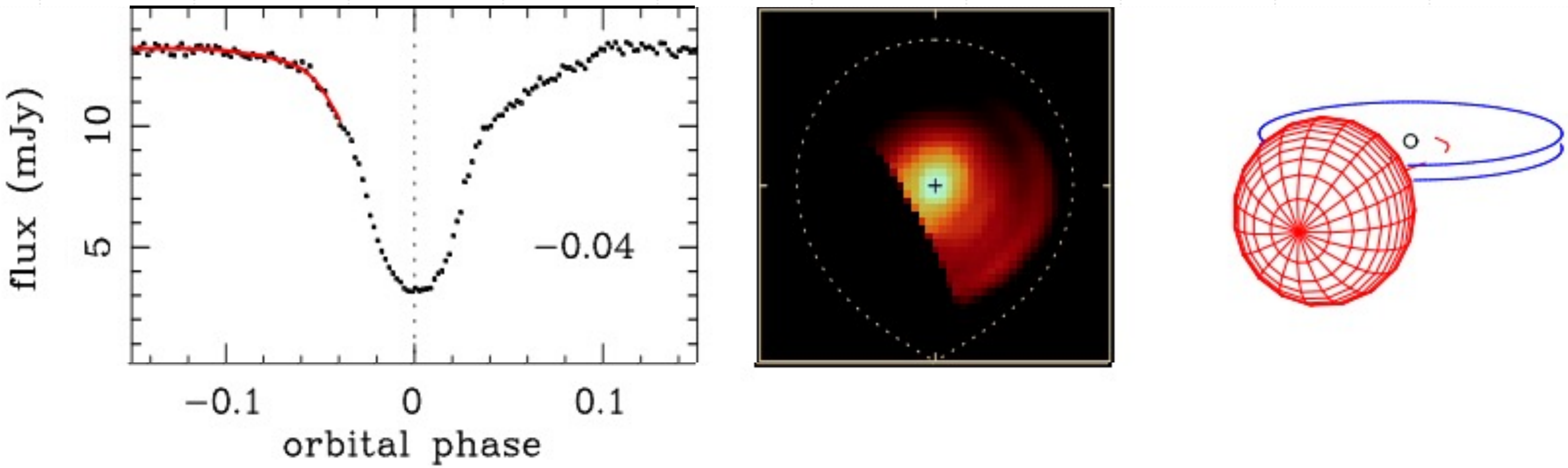
Rutten et al. (1996,1998)

Eclipse mapping: a more complex example



Baptista (2000)

Eclipse mapping: a more complex example



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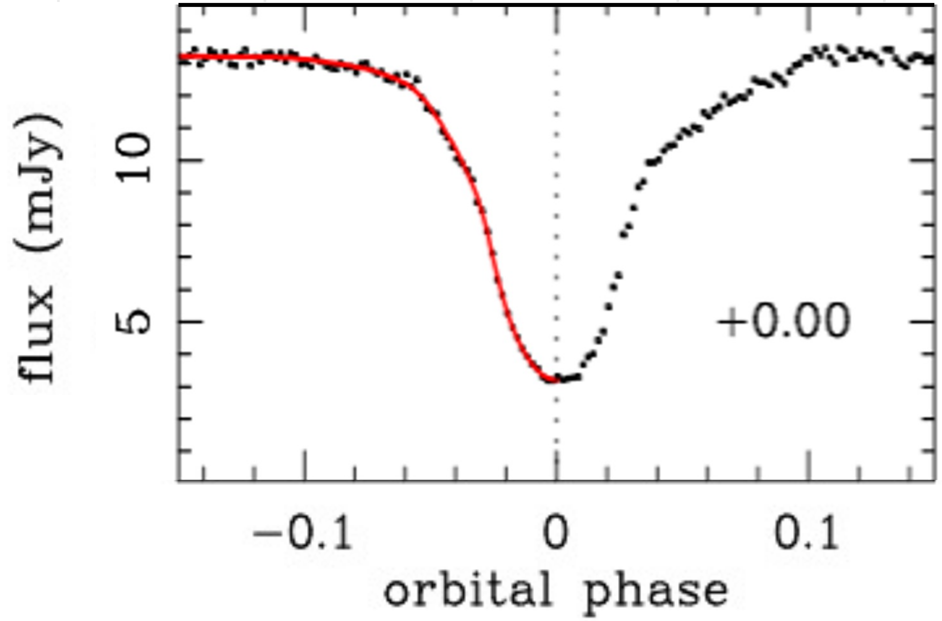

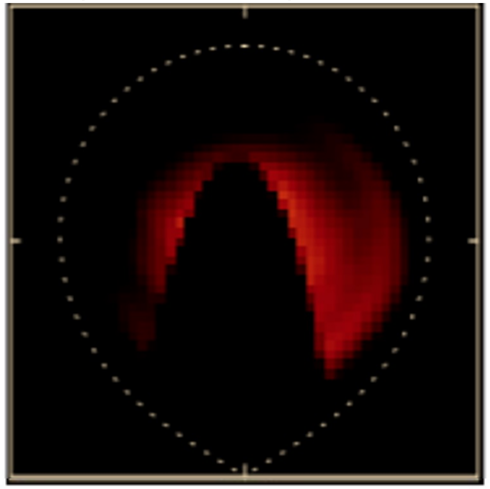

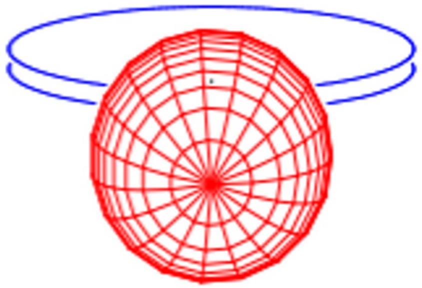

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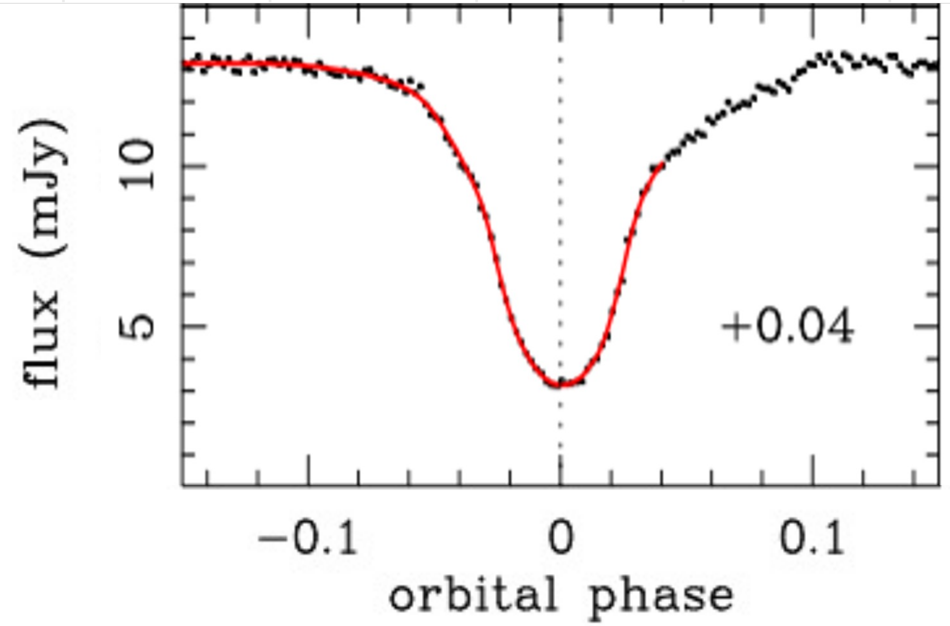

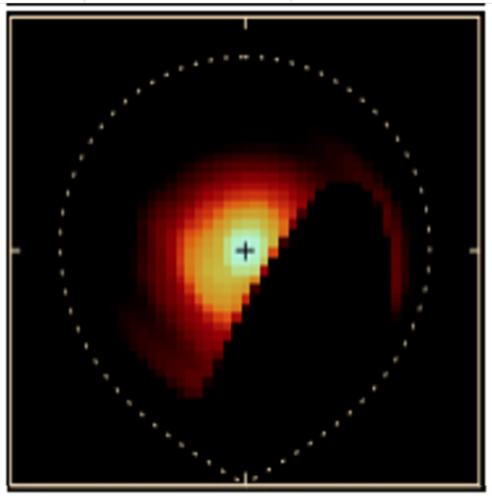

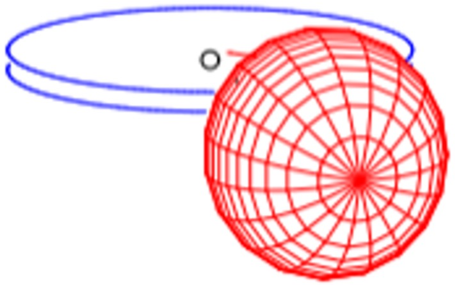

Baptista (2000)

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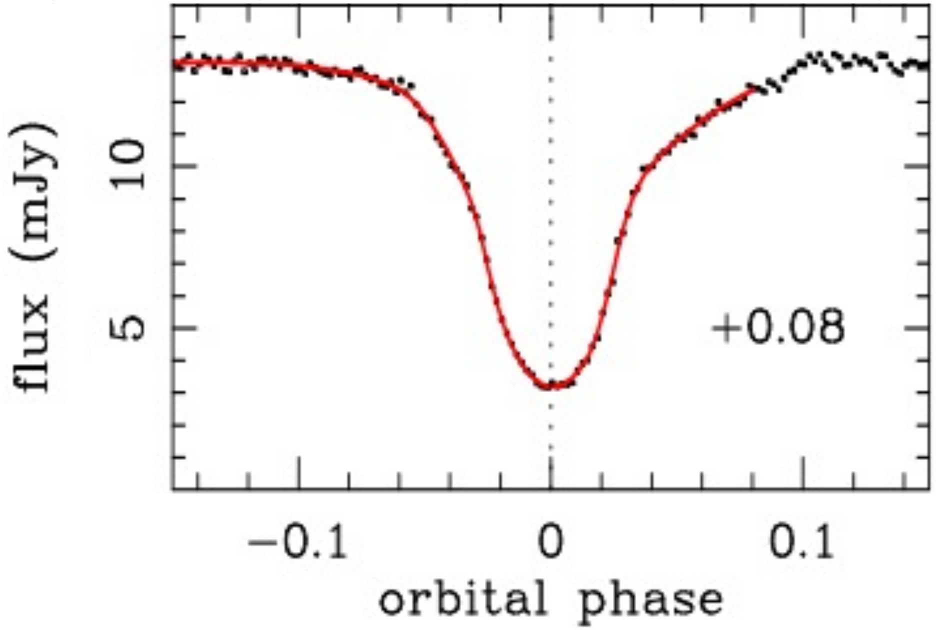
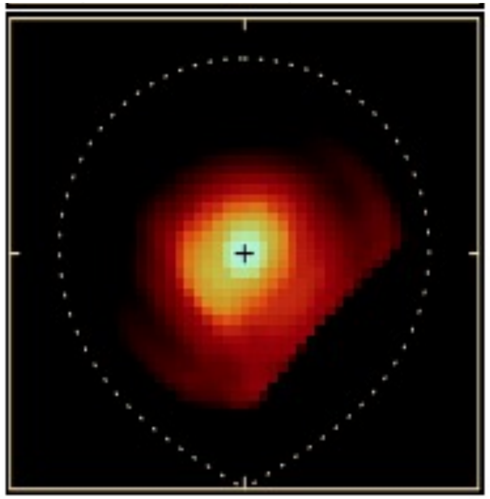
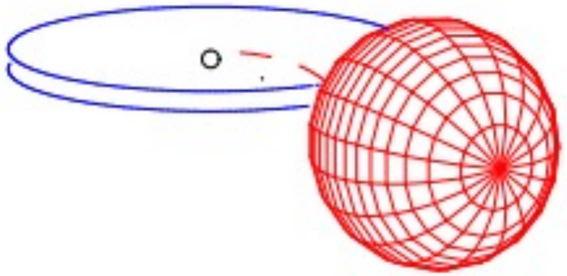
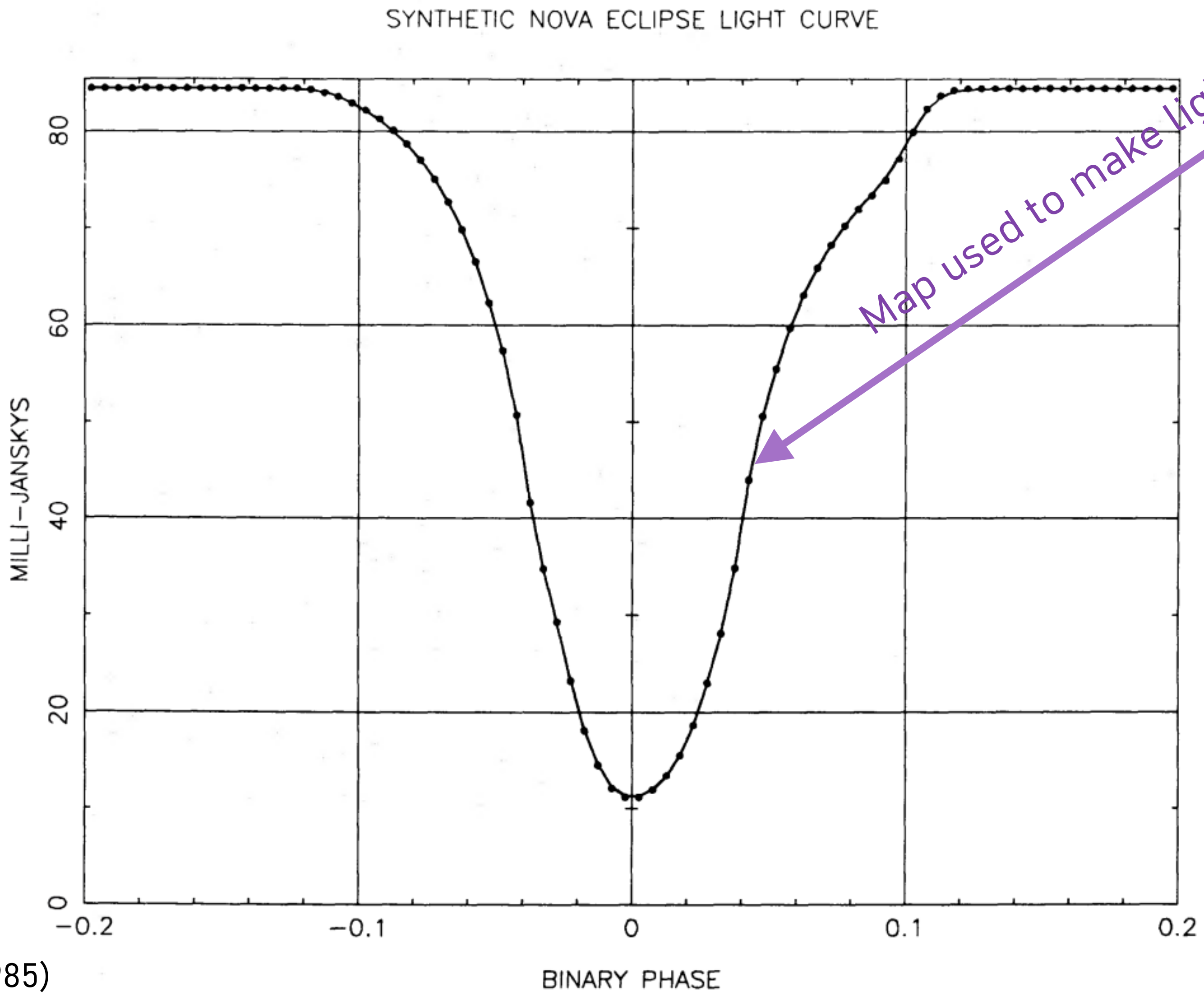


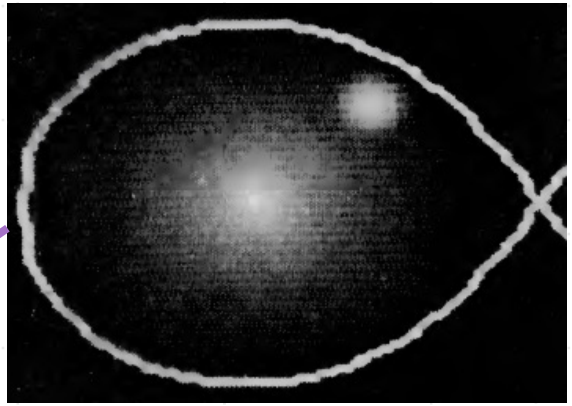




Baptista (2000)

Nuances in creating eclipse maps

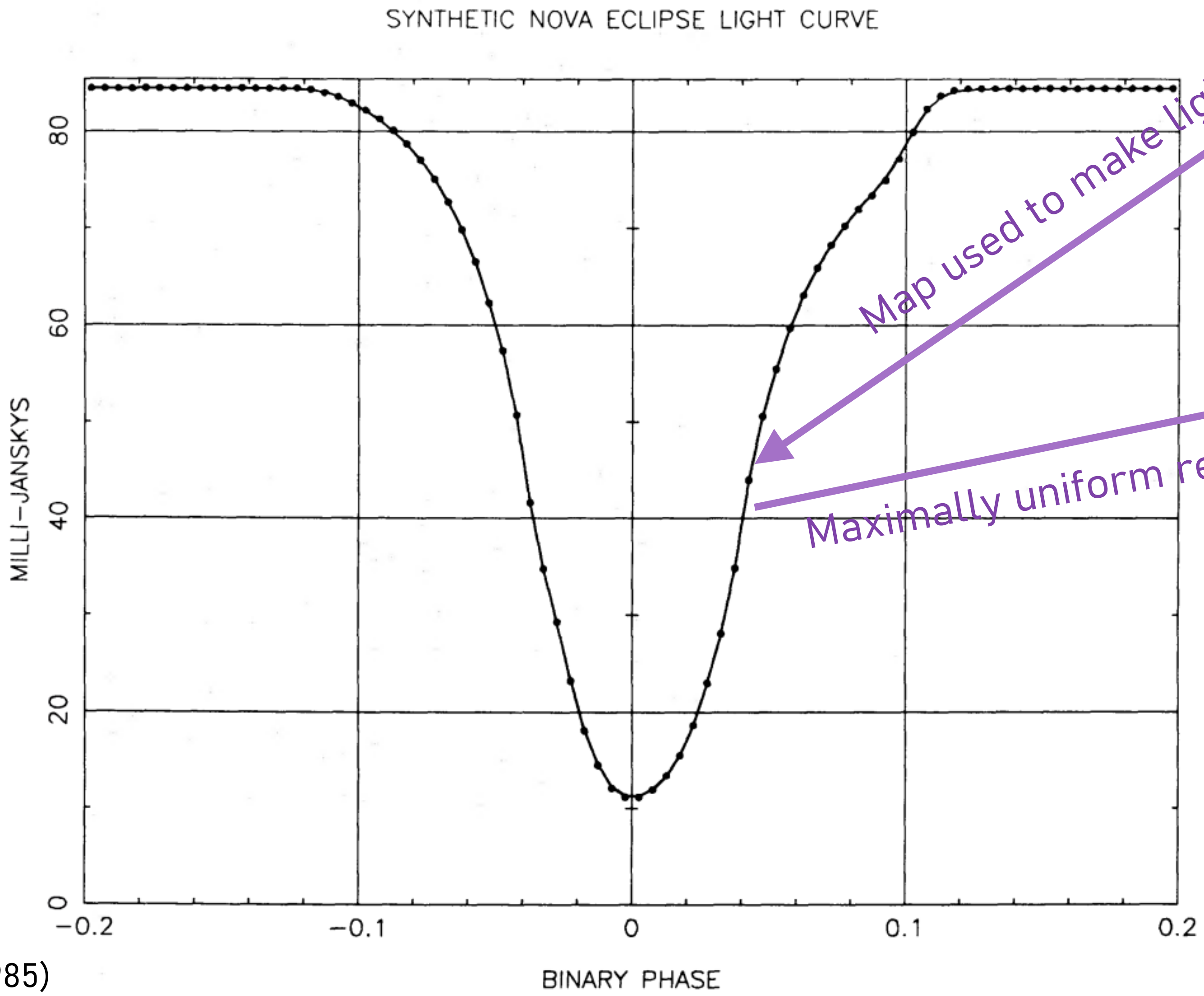




Map used to make light curve

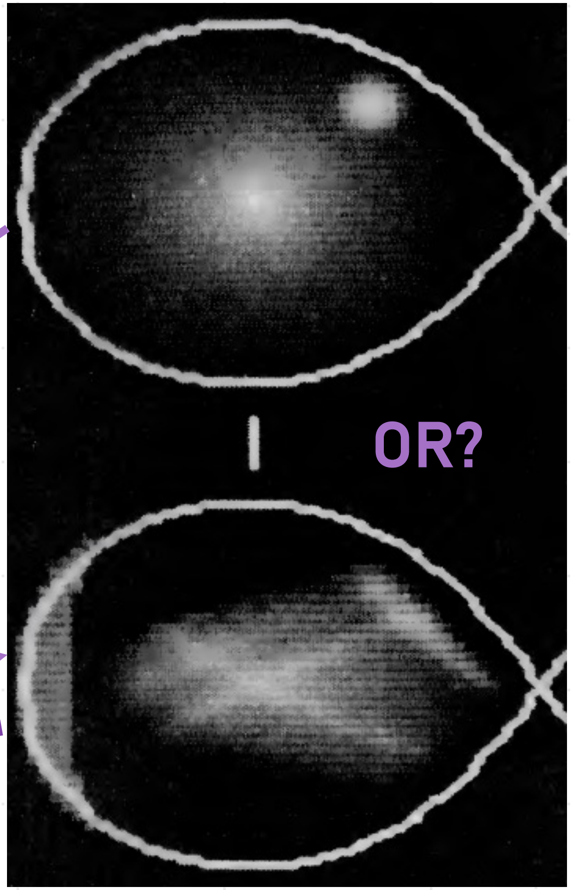
Horne (1985)

Nuances in creating eclipse maps



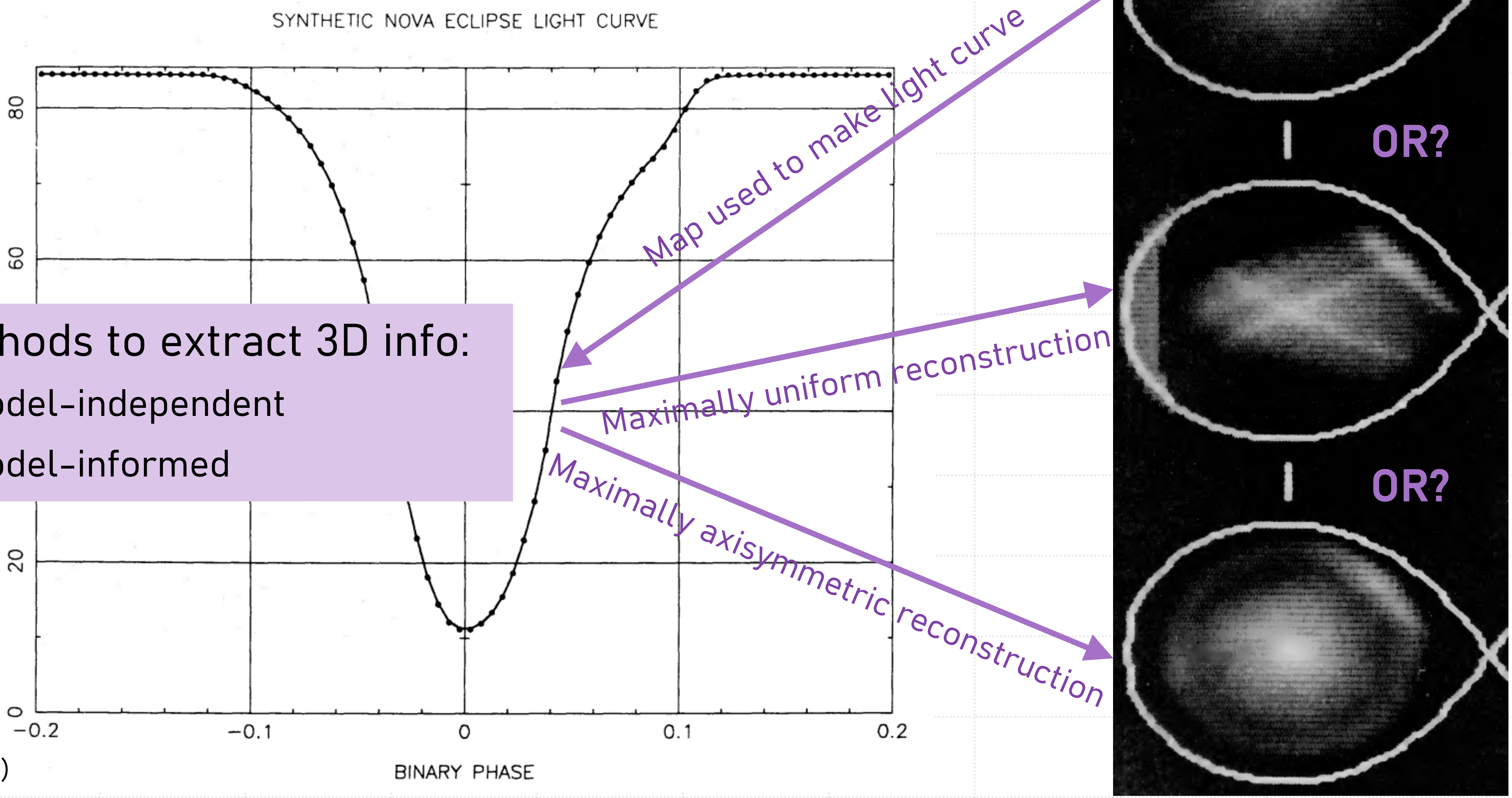
Map used to make light curve

Maximally uniform reconstruction



Horne (1985)

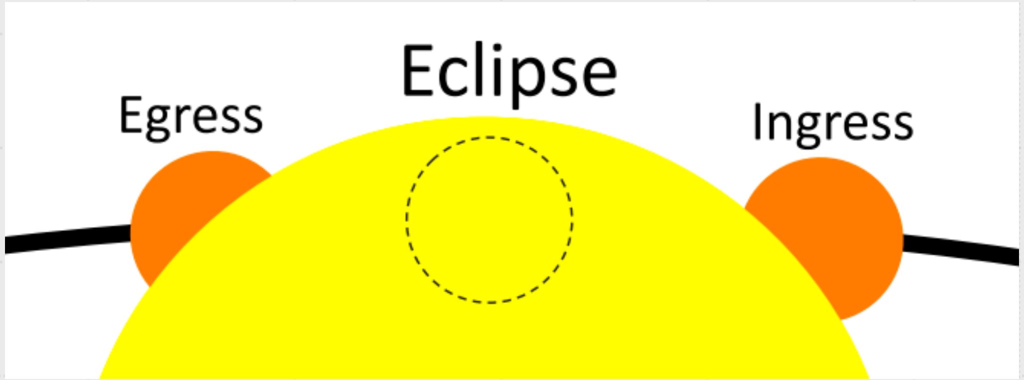
Nuances in creating eclipse maps



- Methods to extract 3D info:
  - Model-independent
  - Model-informed

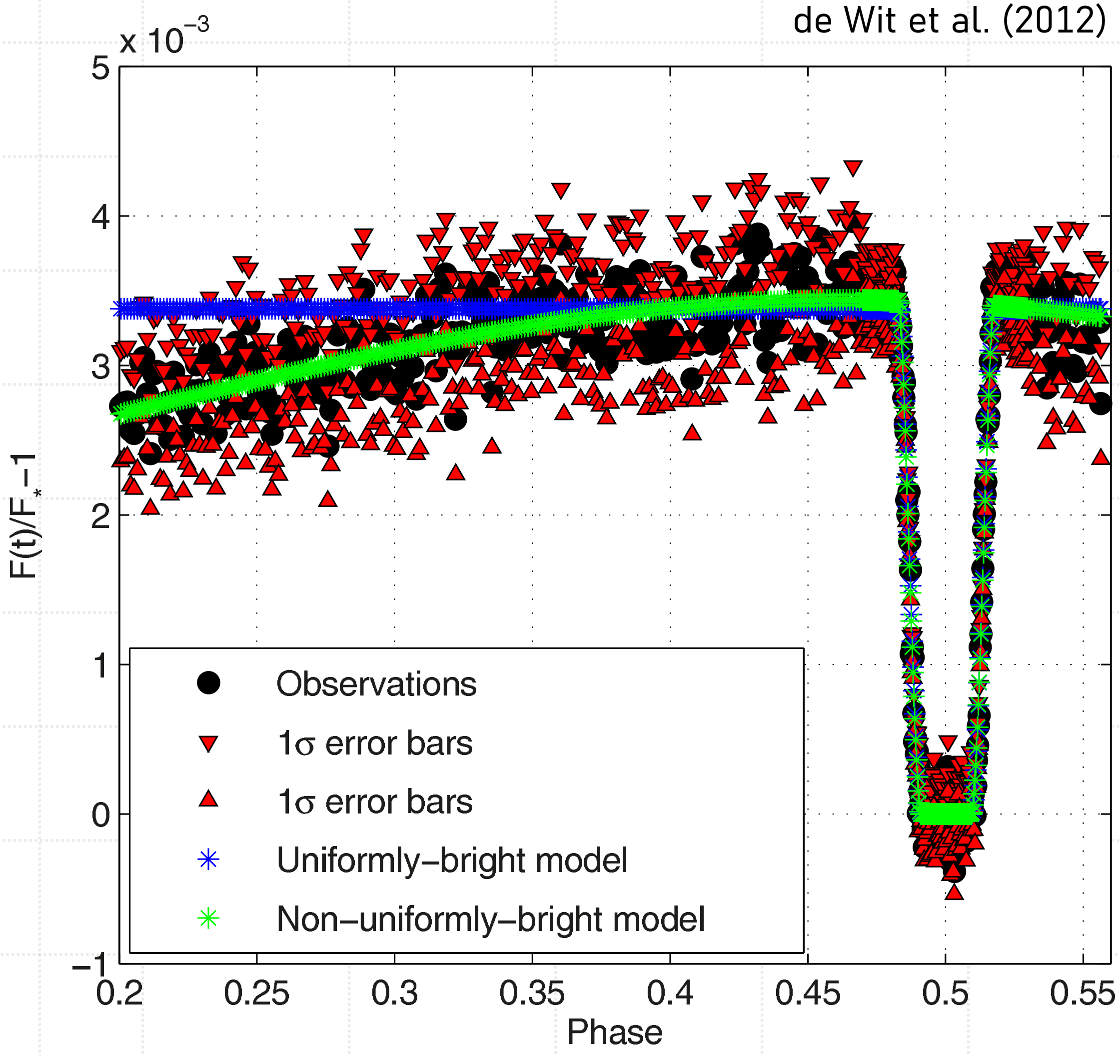
Horne (1985)

Eclipse mapping

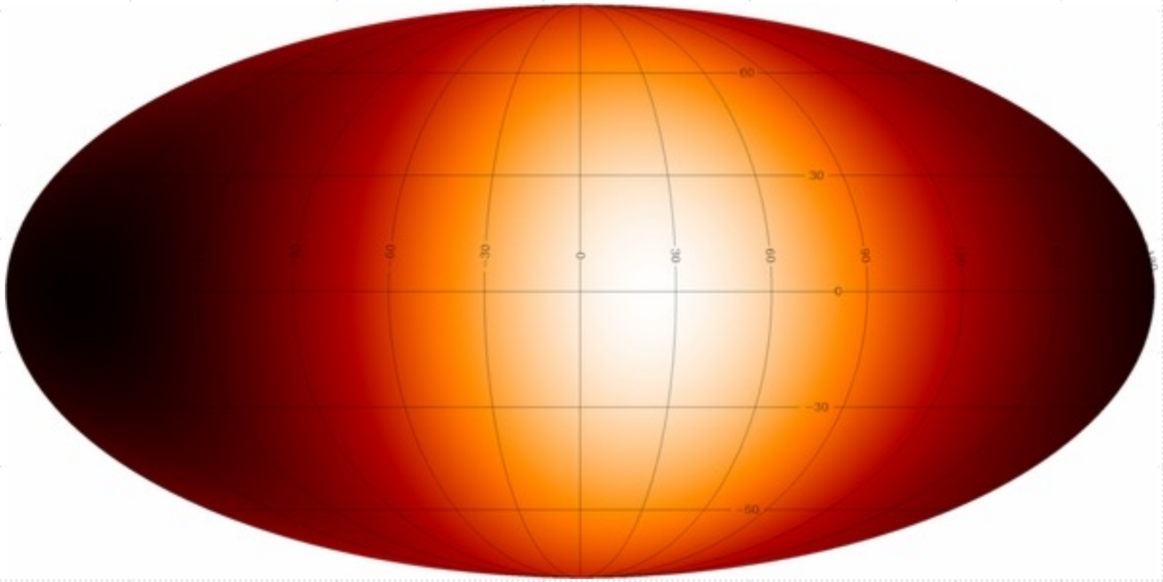


The first (and only) *Spitzer* eclipse map

de Wit et al. (2012)

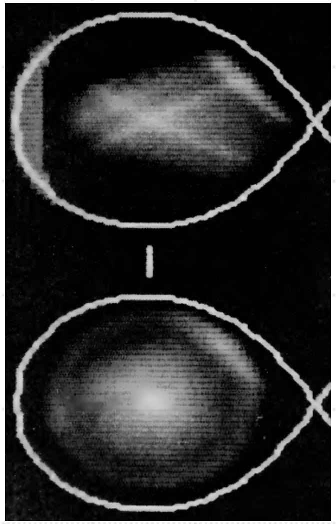


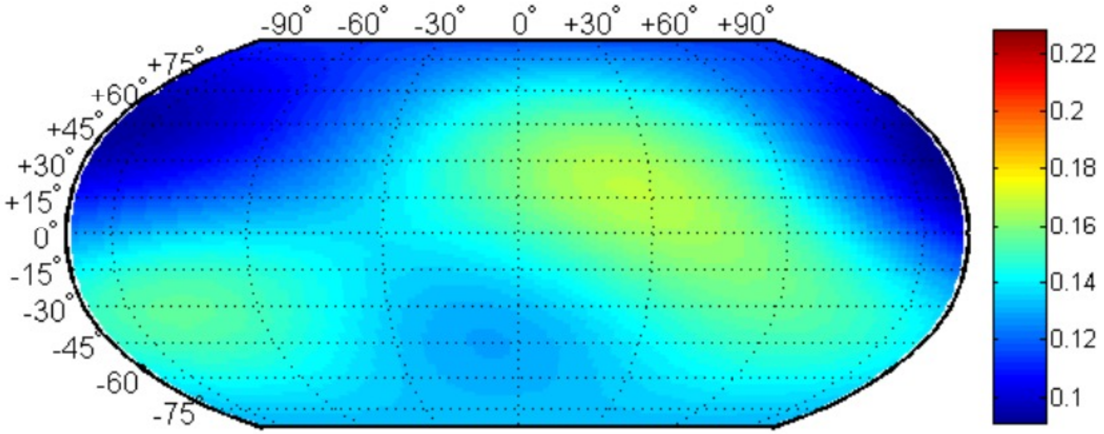
Majeau et al. (2012)



See also Williams et al. (2006); Rauscher et al. (2007)

… but it's complicated … what's the right map to use?

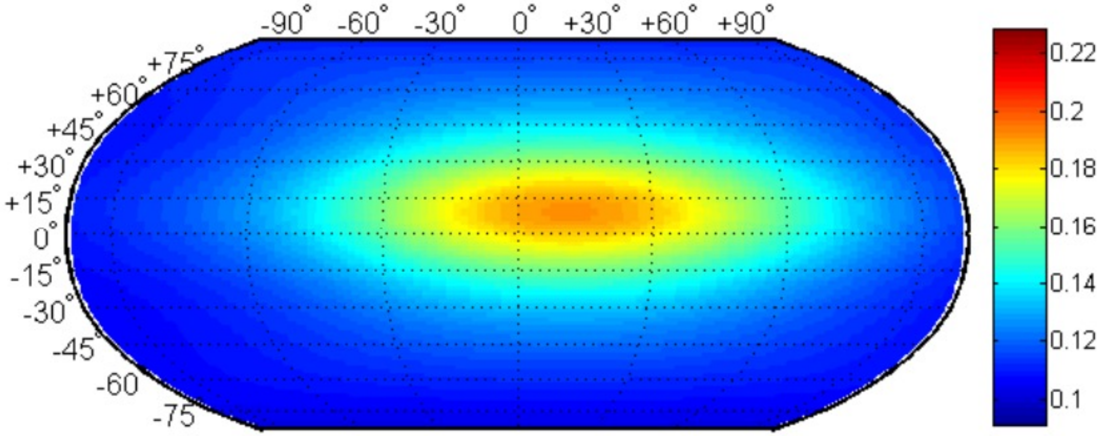




$$\Gamma_{\mathrm{SH},3}(\phi,\theta) = \sum_{l=0}^{3} I_l Y_l^0(\phi - \Delta\phi_l, \theta - \Delta\theta_l),$$

Spherical harmonics

OR?



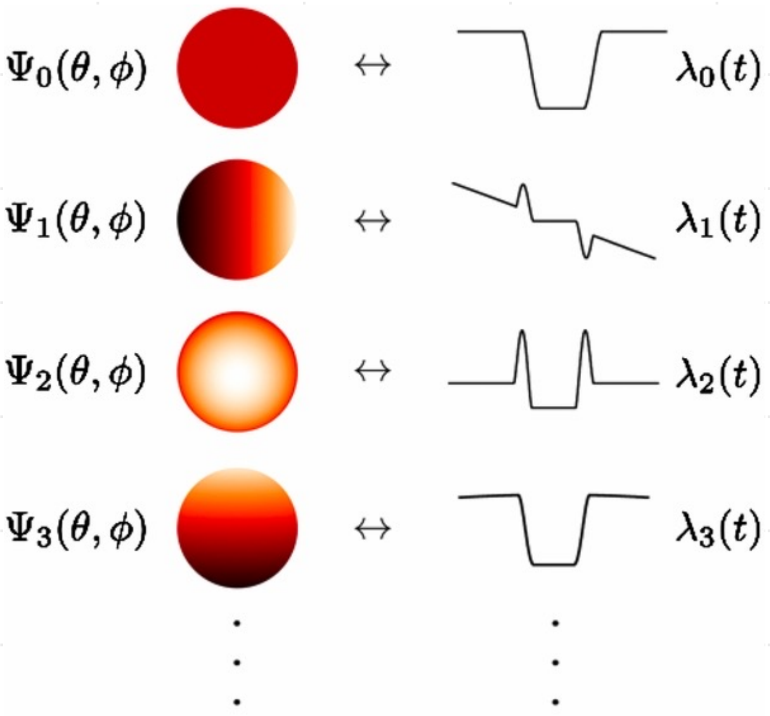
A physical assumption about how the planet should look

$$\Gamma_2(\phi,\theta) = \begin{cases} I_1 \cos^{\alpha}\phi_\circ \cos^{\gamma}\theta_\circ + I_0 & \text{if } \phi_\circ \geq 0 \\ I_1 \cos^{\beta}\phi_\circ \cos^{\gamma}\theta_\circ + I_0 & \text{if } \phi_\circ < 0, \end{cases}$$

de Wit et al. (2012)

"Eigen-mapping": a model-independent method

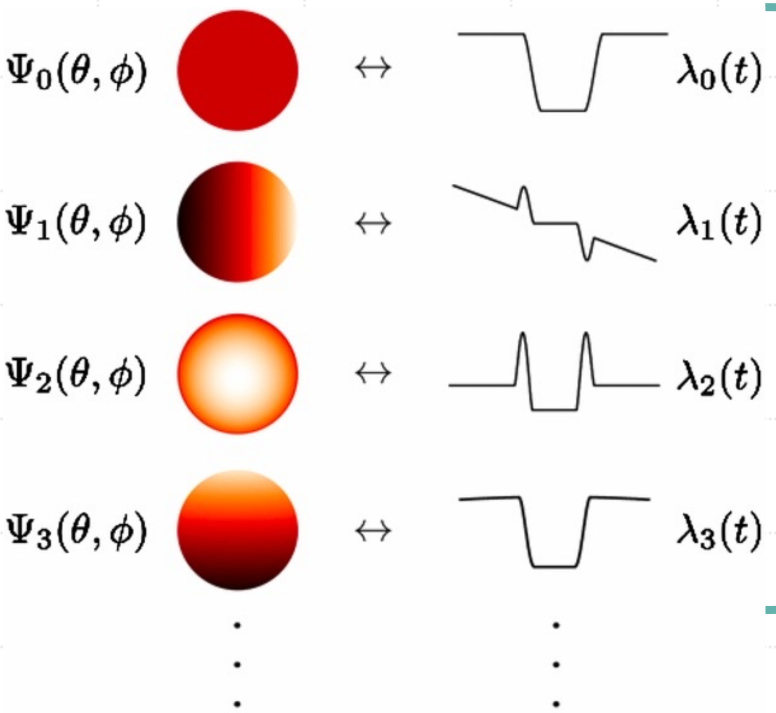
orthogonal on the planet ⟷ **NOT orthogonal in the data**



Majeau et al. (2012)

"Eigen-mapping": a model-independent method

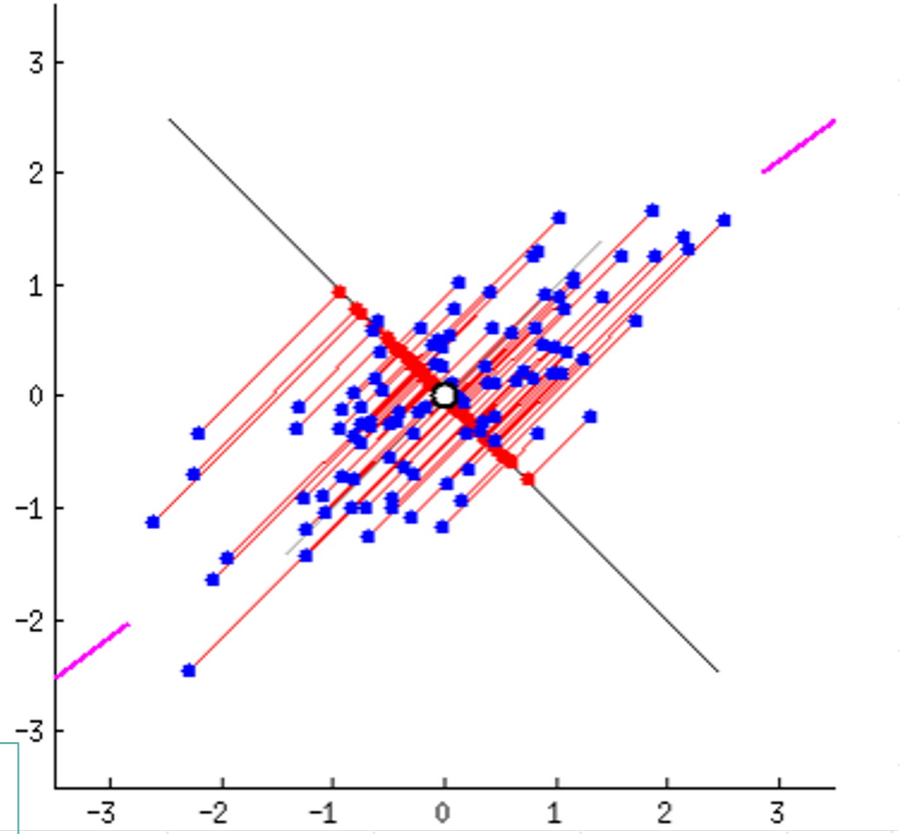
Spherical harmonic light curves, $F_l^m(t)$



Majeau et al. (2012)

Principal Component Analysis

Identifies orthogonal and maximally informative light curves



From: https://medium.com/analytics-vidhya

"Eigen-mapping": a model-independent method

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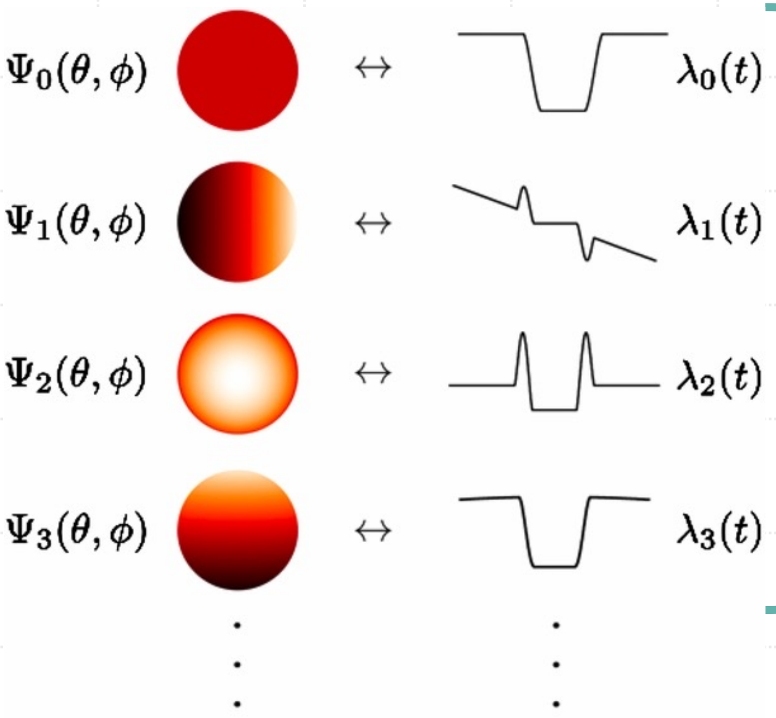
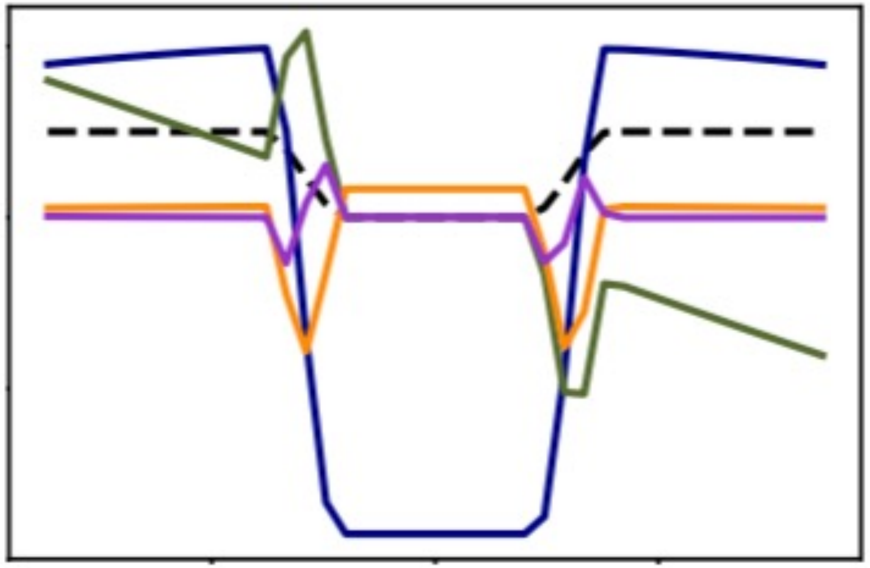


Majeau et al. (2012)

$\lambda_{n,l,m}$

Principal Component Analysis

"Eigen-curves", $E_n(t)$

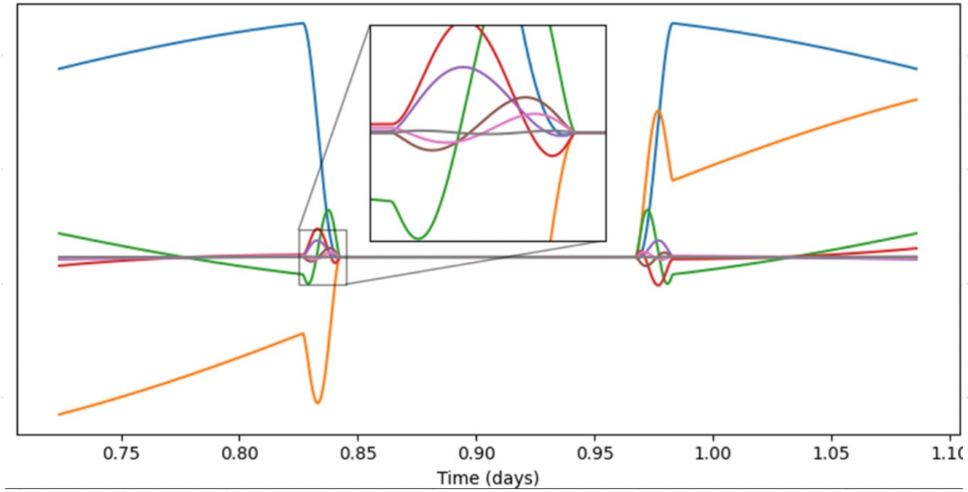


Rauscher et al. (2018)

$$E_n(t) = \sum_{l=1}^{l_{\max}} \sum_{m=0}^{\pm l} \lambda_{n,l,m} F_l^m(t)$$

"Eigen-mapping": a model-independent method

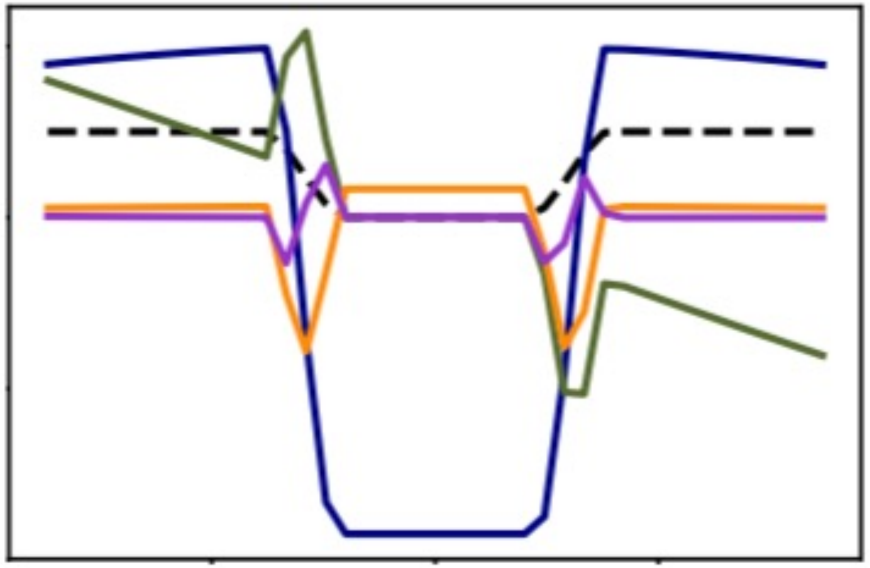
"Eigen-maps", $Z_n(\theta, \phi)$



Challener & Rauscher (2022)
ThERESA code available on github

$\lambda_{n,l,m}$

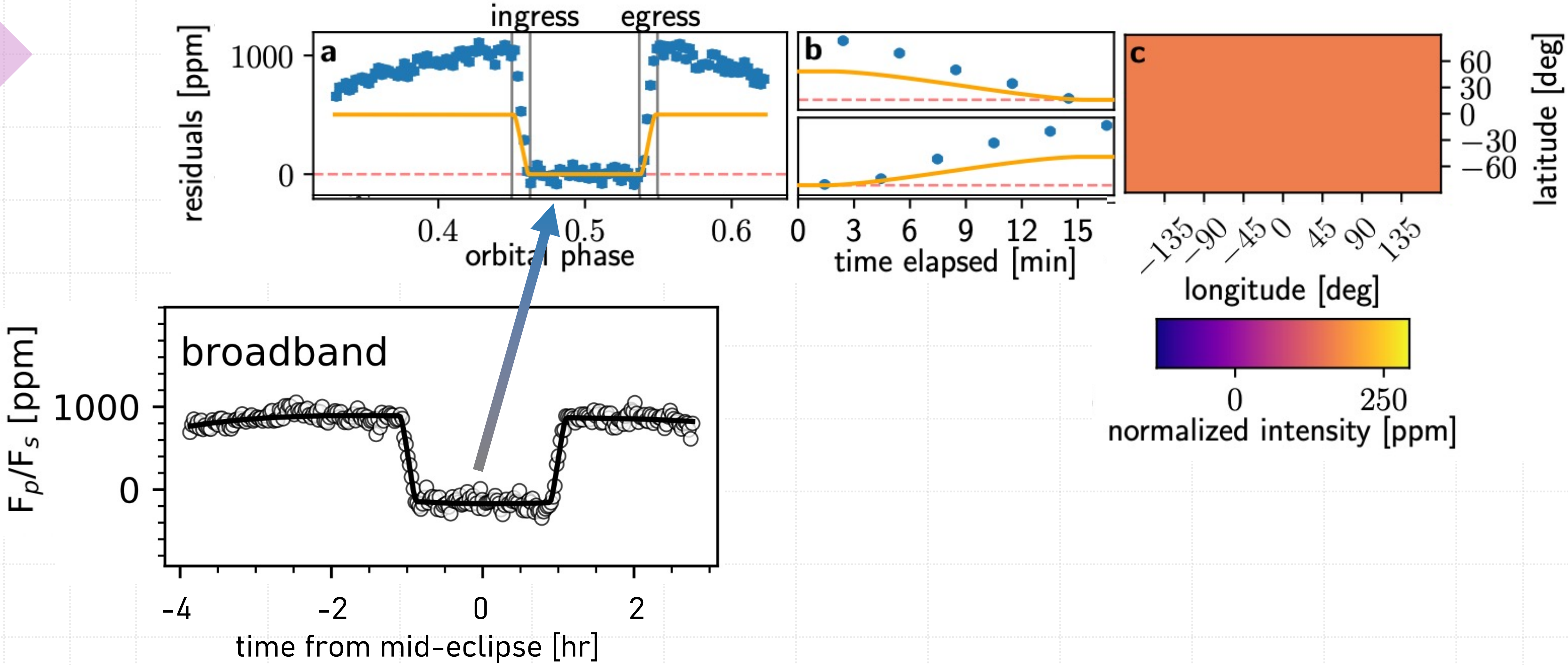
"Eigen-curves", $E_n(t)$



Rauscher et al. (2018)

$$Z_n(\theta, \phi) = \sum_{l=1}^{l_{\max}} \sum_{m=0}^{\pm l} \lambda_{n,l,m} Y_l^m(\theta, \phi)$$

The *first* eclipse map with JWST!



JWST ERS Transiting Exoplanets Team, Coulombe et al. (2023)

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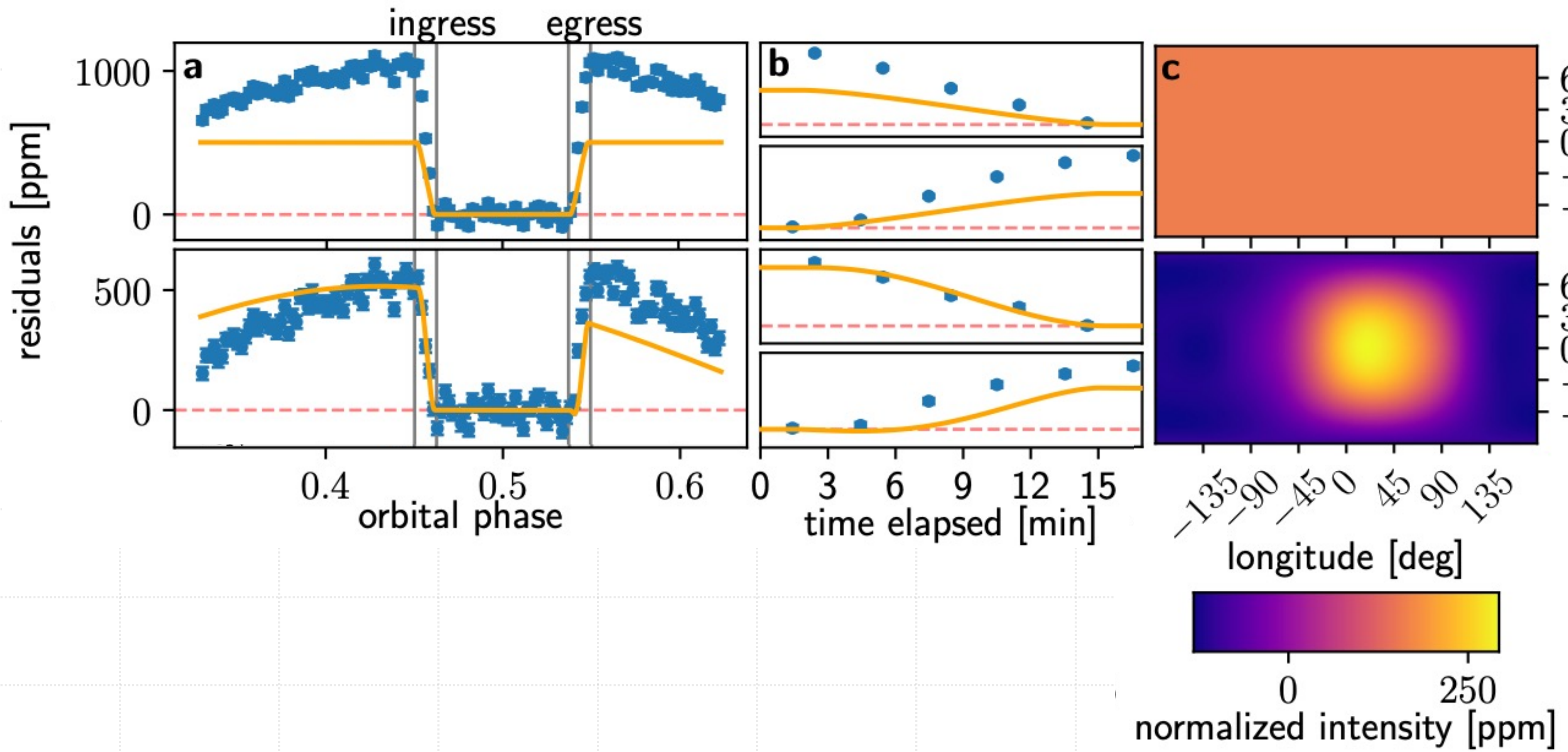

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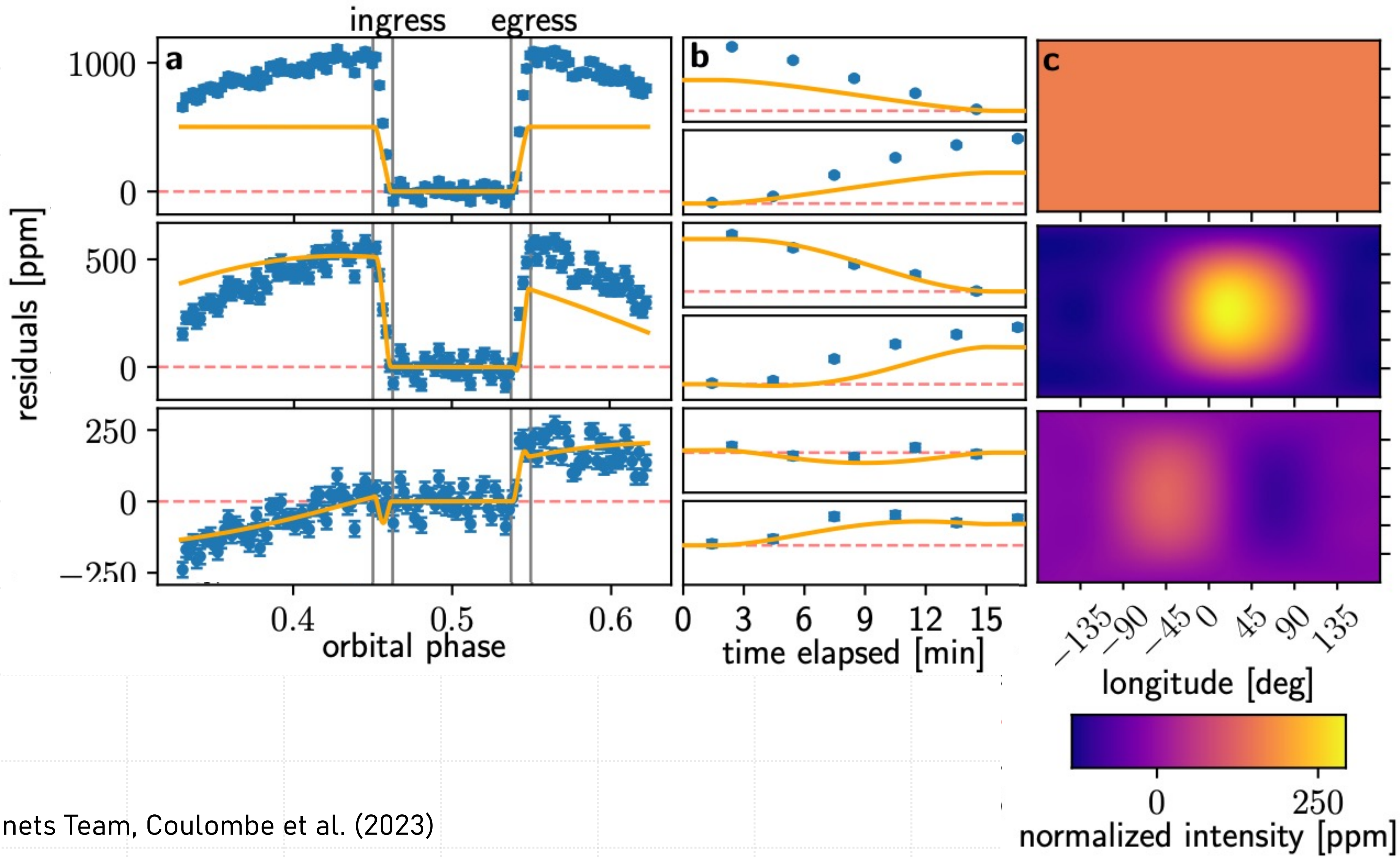

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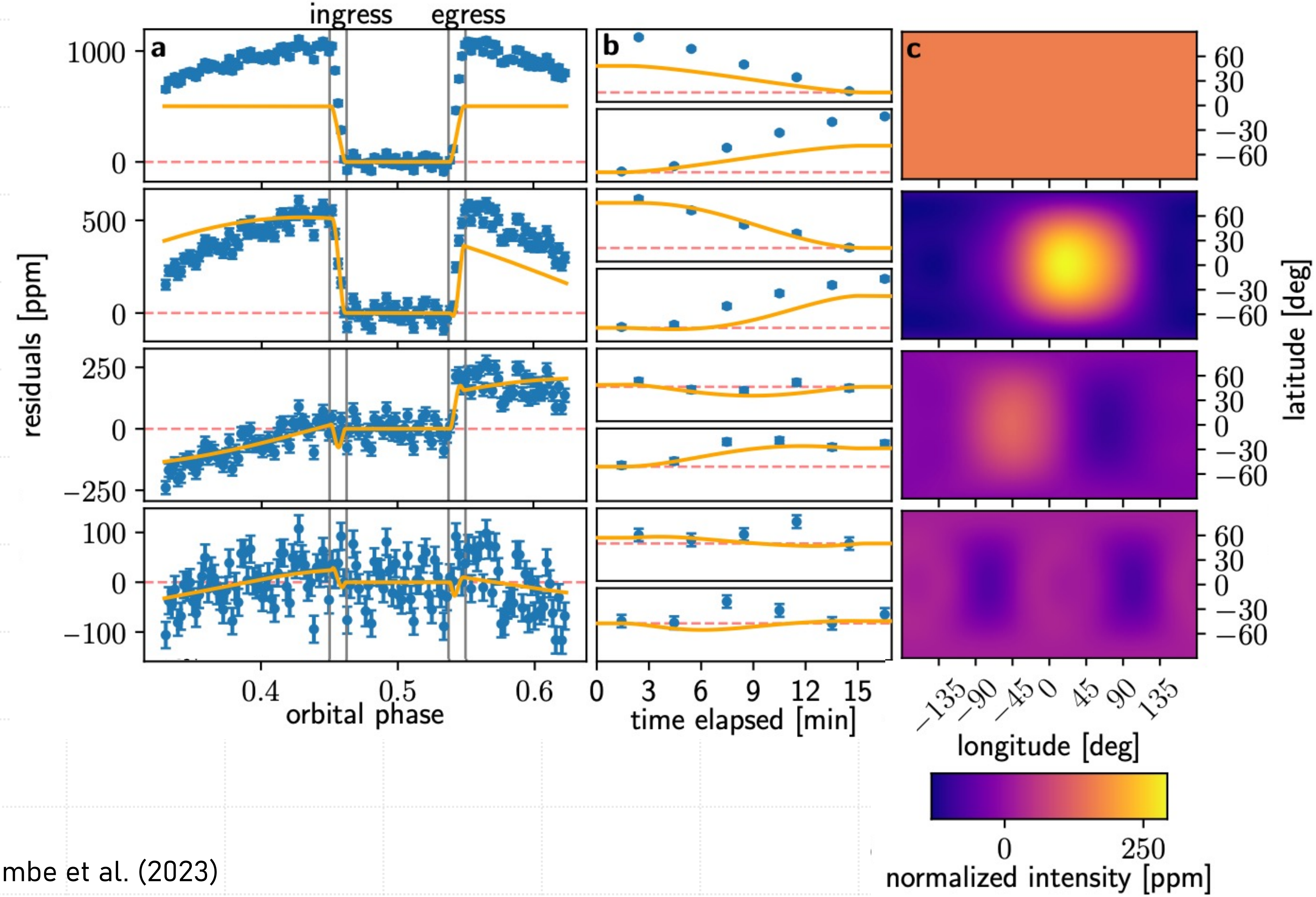

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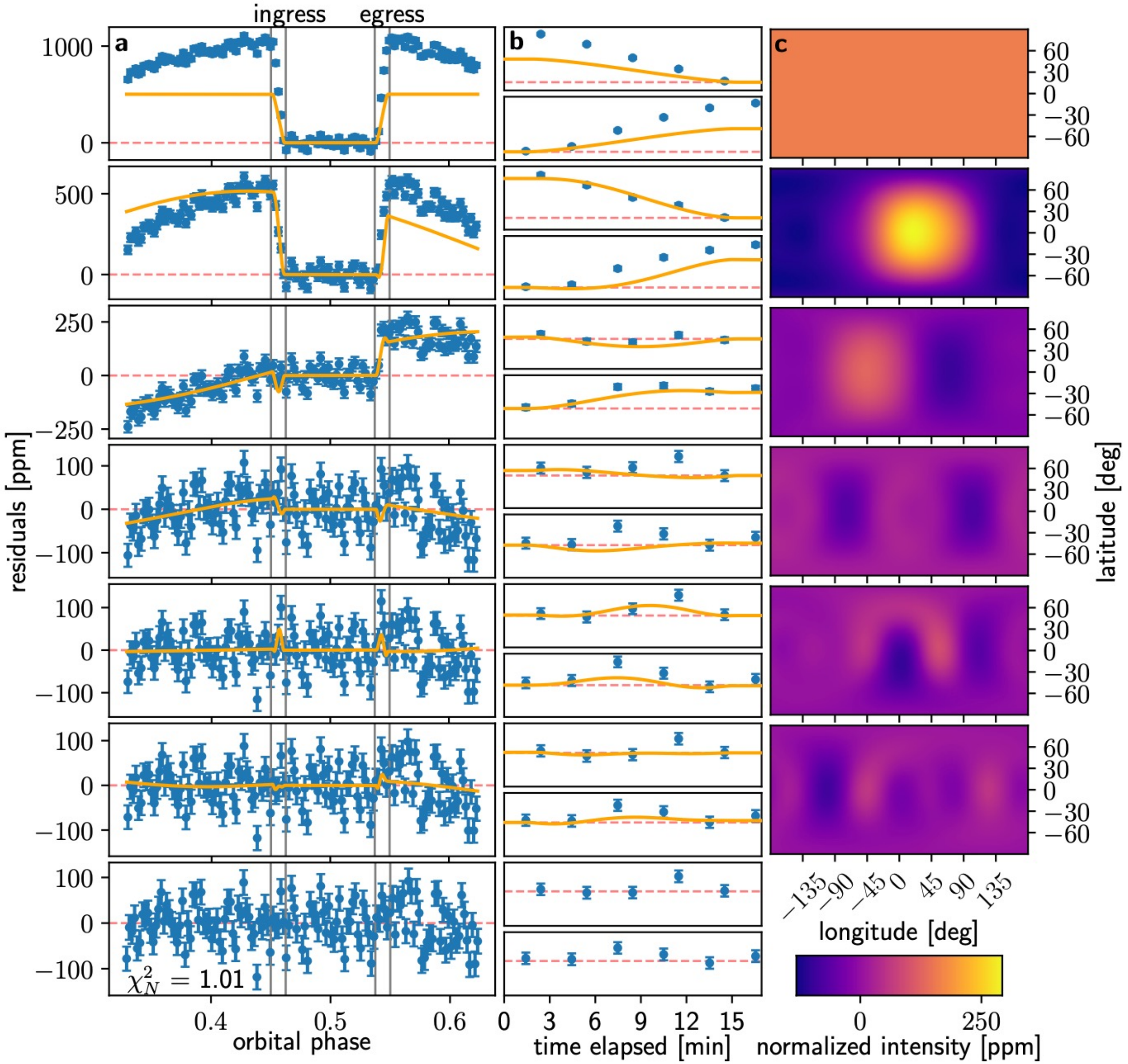

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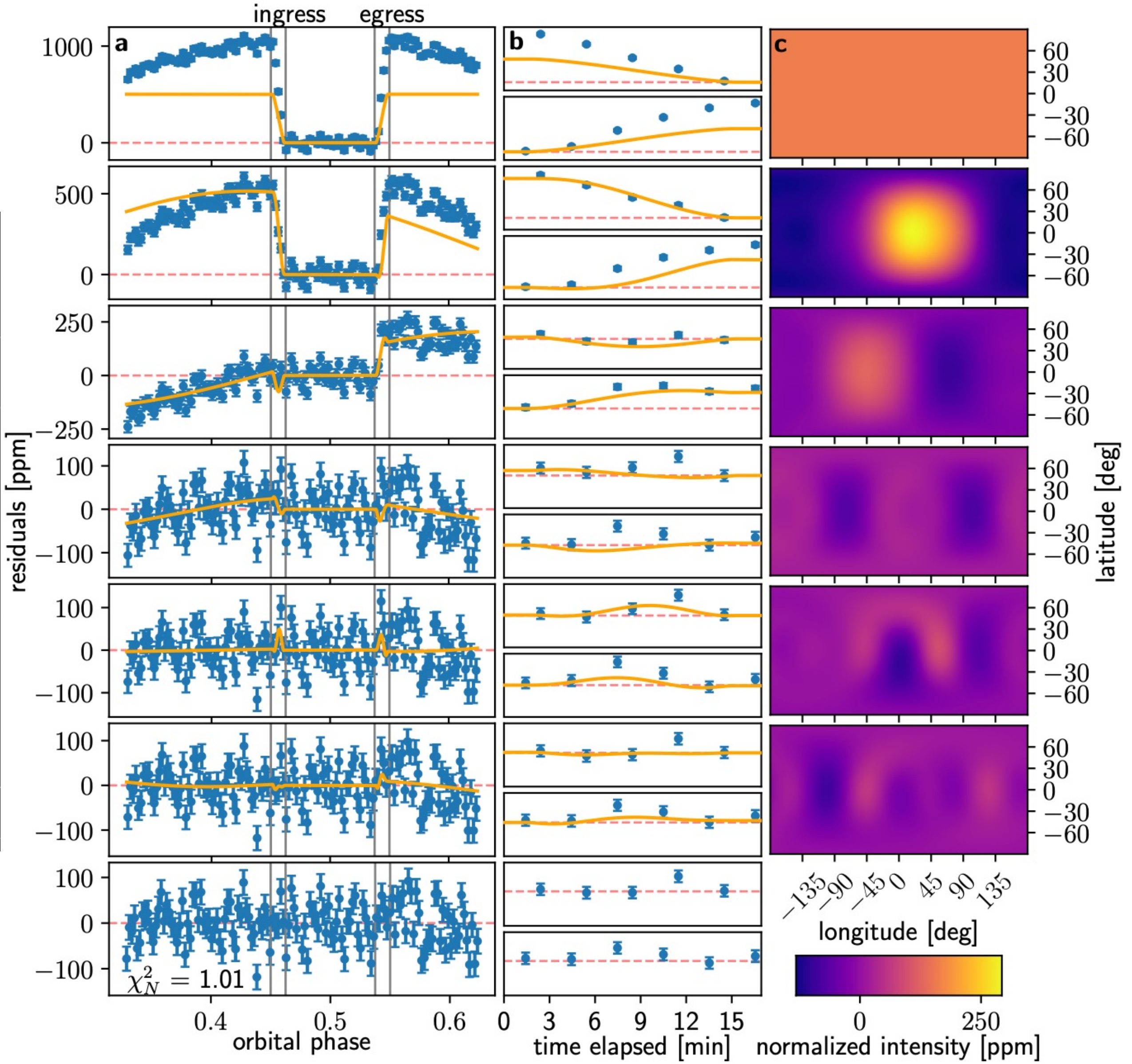
The *first* eclipse map with JWST!

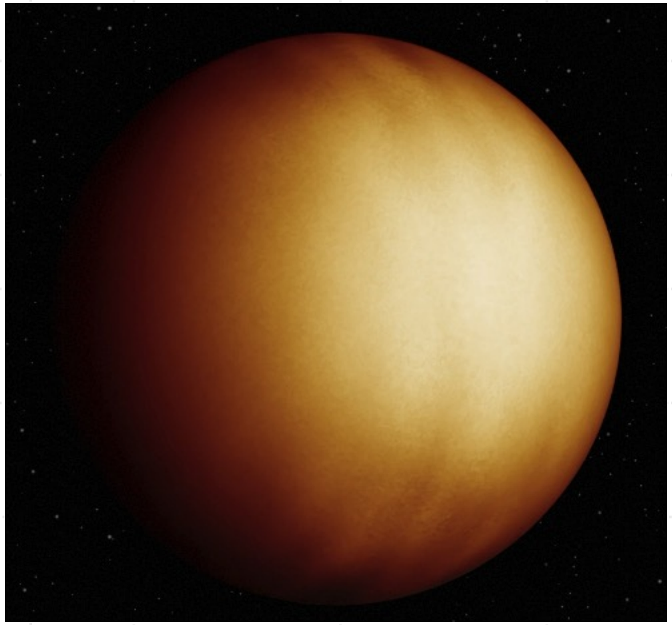
Credit: NASA/JPL-Caltech (K. Miller/IPAC)

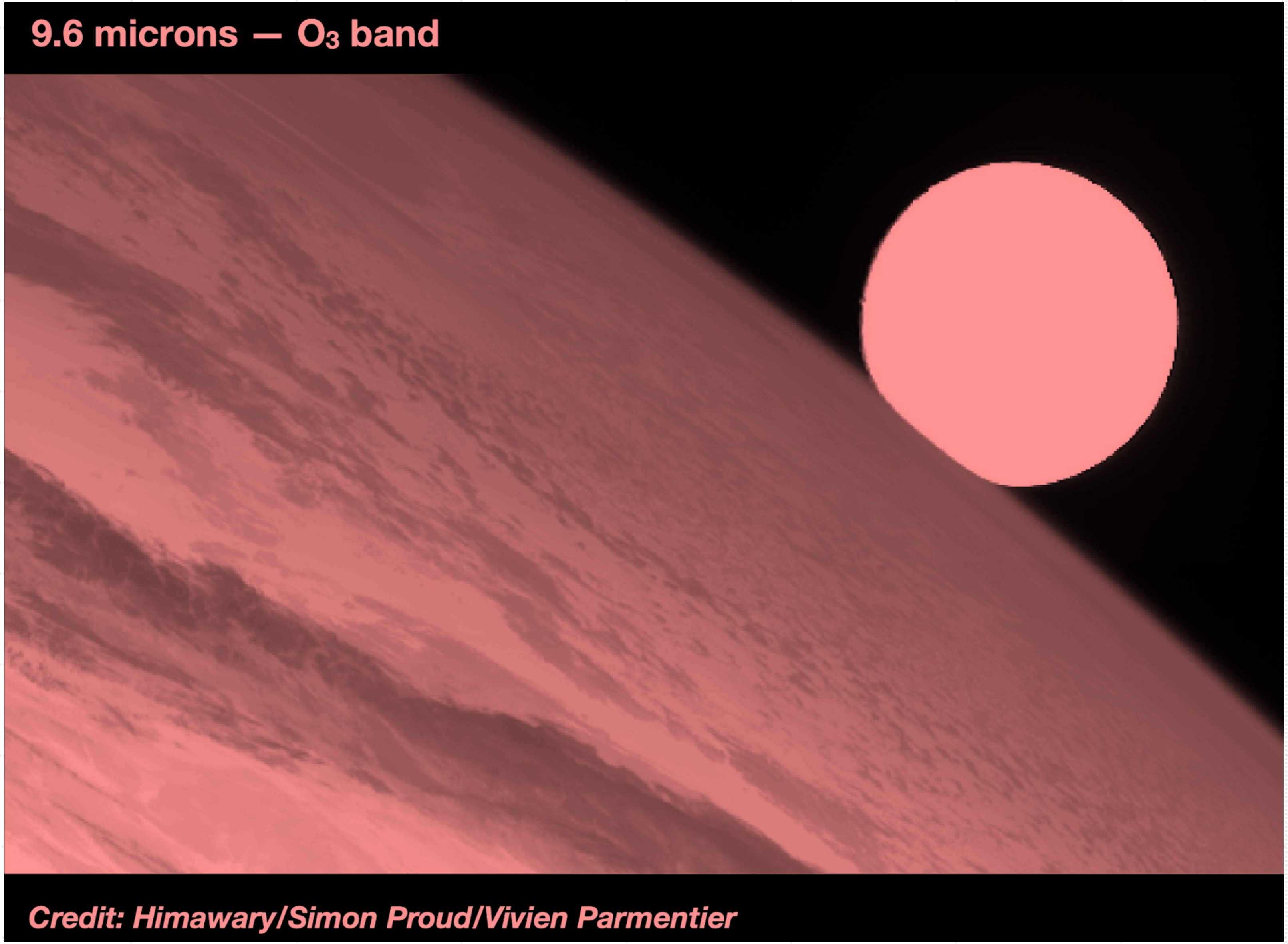


JWST ERS Transiting Exoplanets Team, Coulombe et al. (2023)

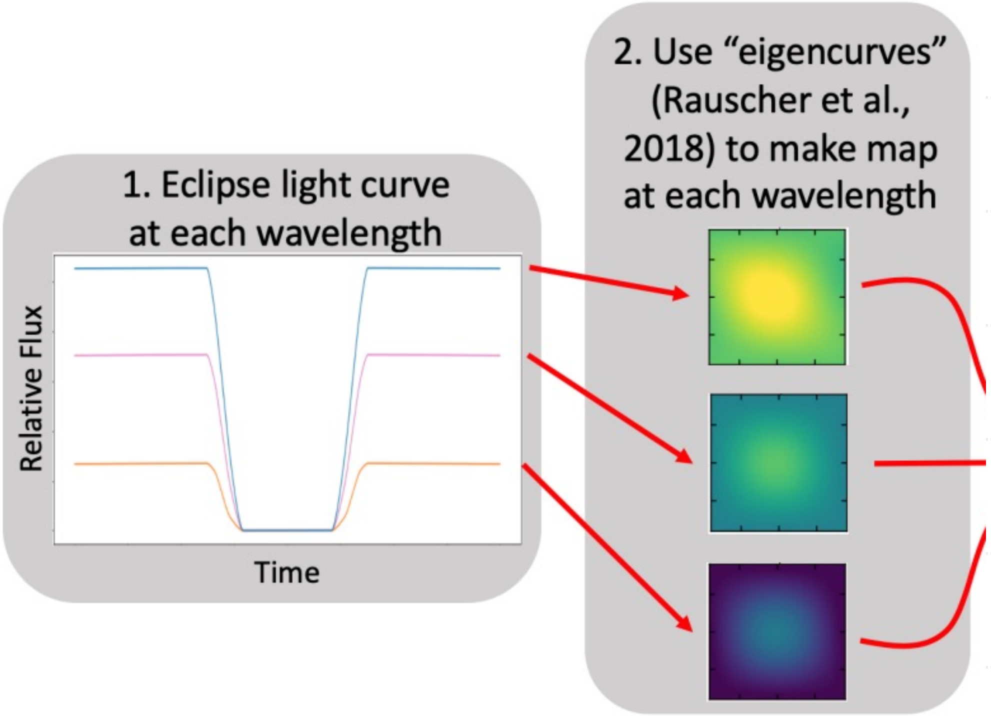
But what about a 3D map?

- Thermal emission comes from different layers in the atmosphere



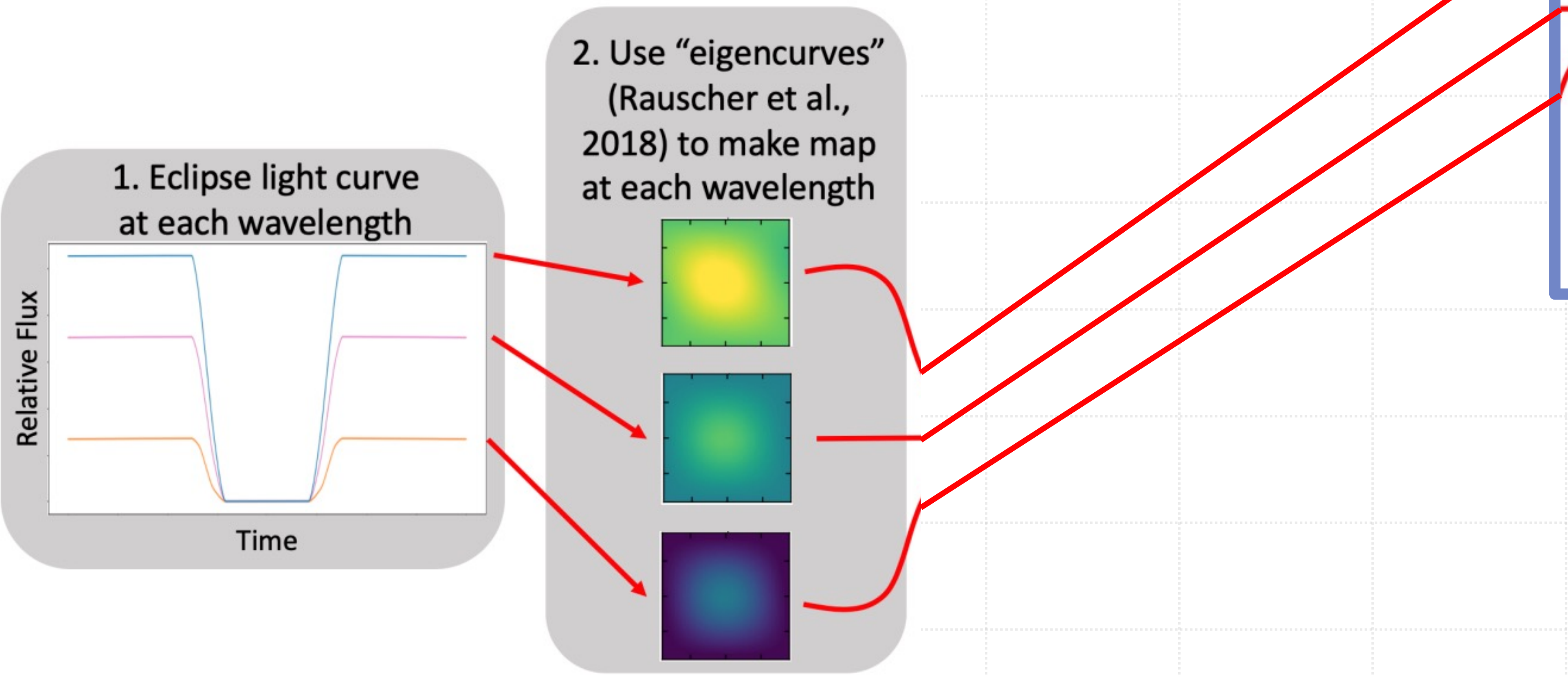


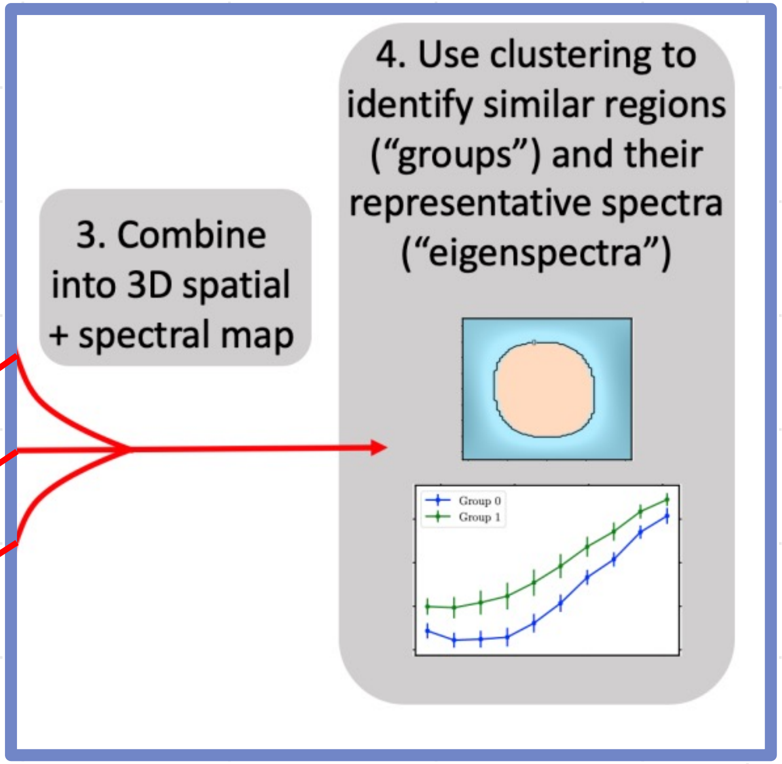
3D Eclipse Mapping Methods:



Mansfield et al. (2020)

3D Eclipse Mapping Methods:
Model-independent spectral-spatial groups





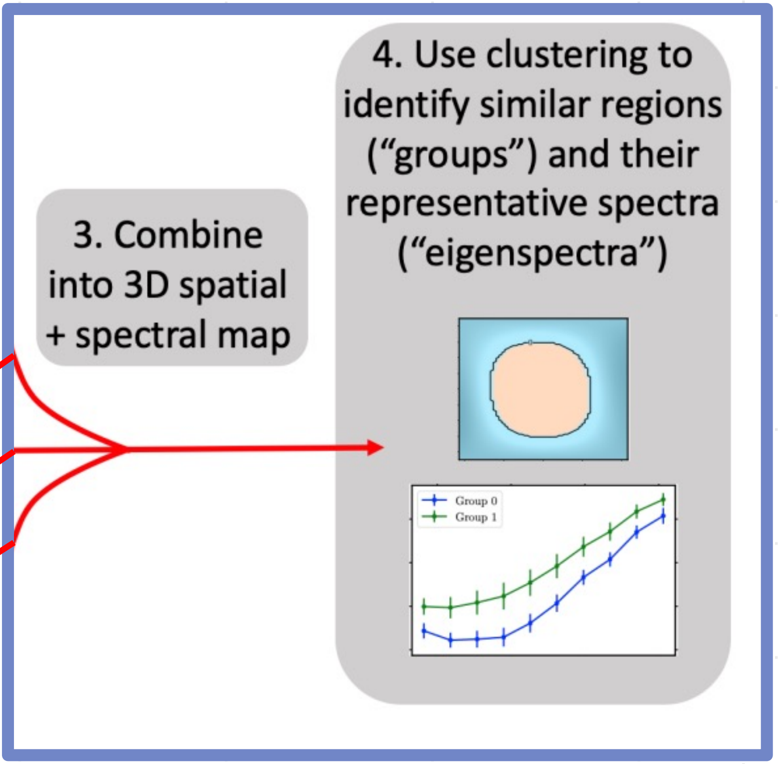
3D Eclipse Mapping Methods:

Model-independent spectral-spatial groups

OR

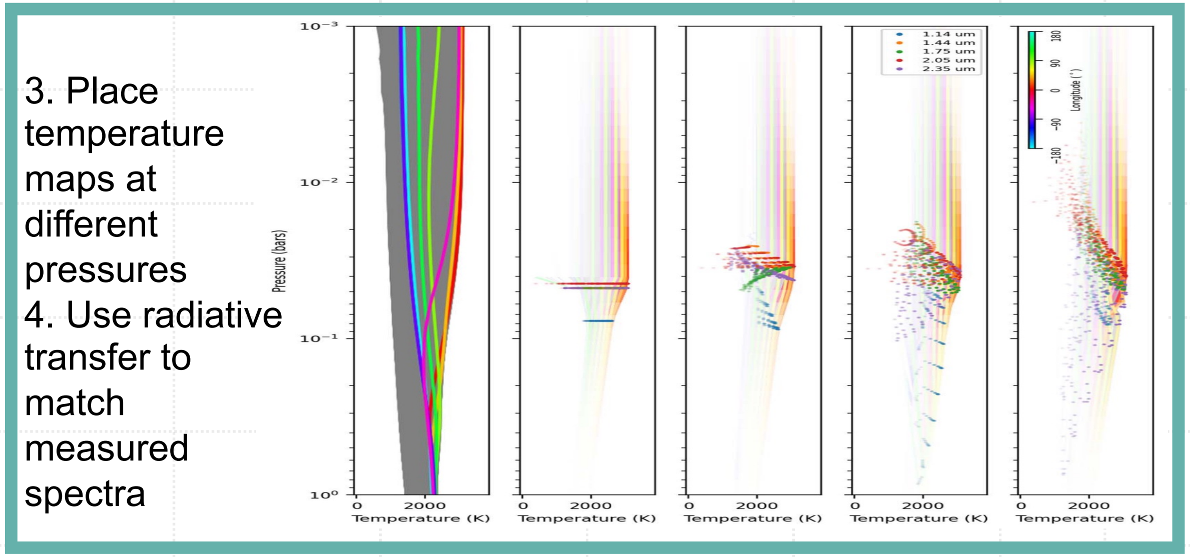
Temperature-pressure parameterization

Mansfield et al. (2020)



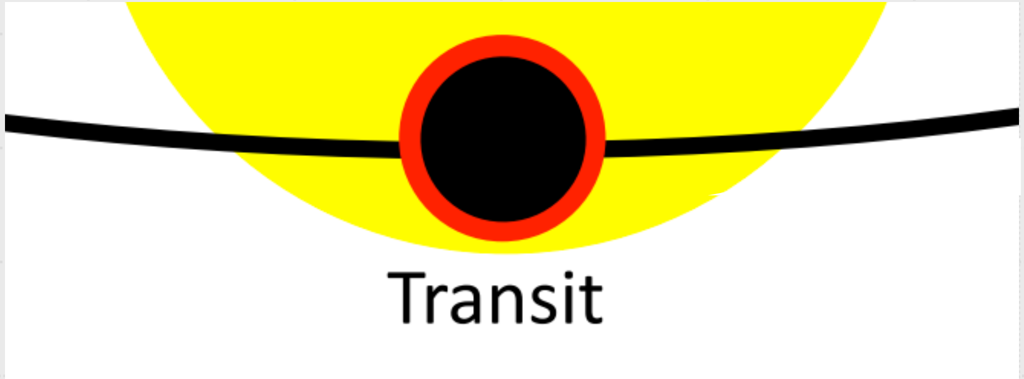
Stay tuned!

- 3D map of WASP-18b
- More maps:
  - WASP-43b
  - GTO/GO targets
- More techniques
  - parameterizations linking temperature structure to physics
  - what parts of a map we *can't* see (null space)



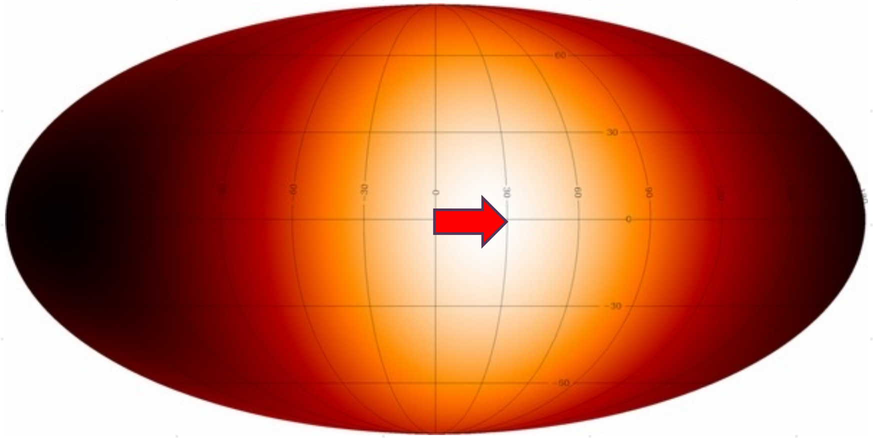
Challener & Rauscher (2022)

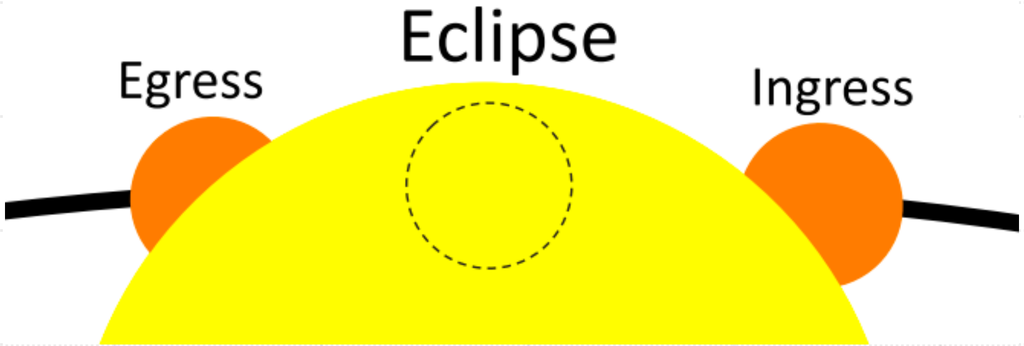
Transit mapping



How spatial structure shows up in transit

Dayside facing us





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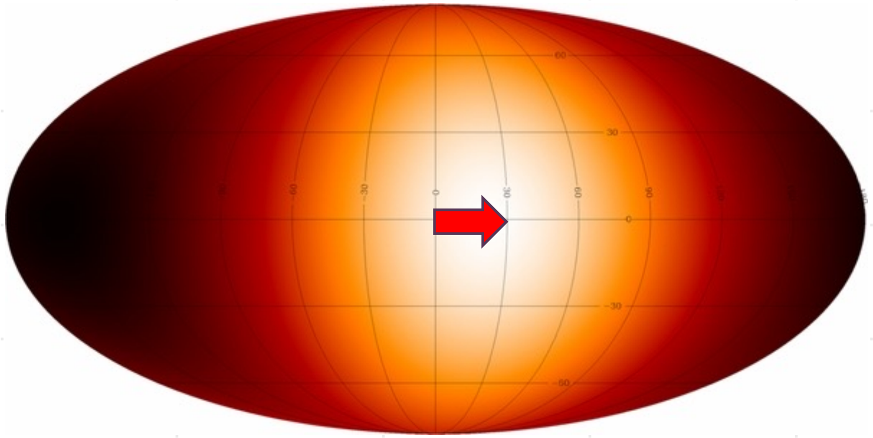
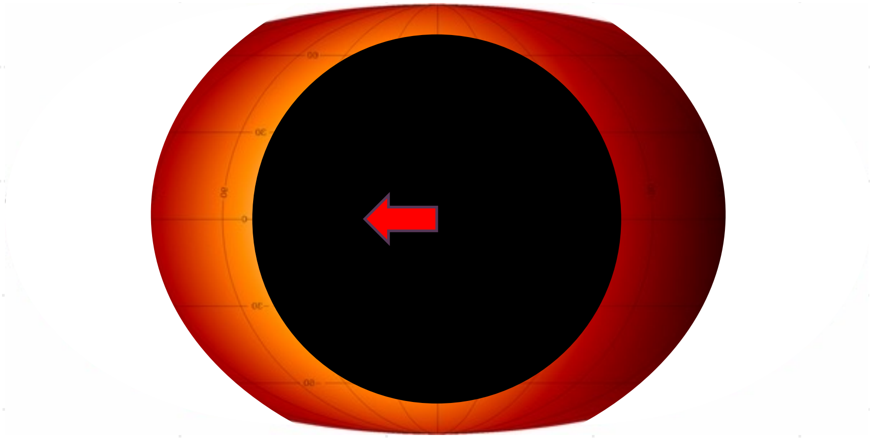
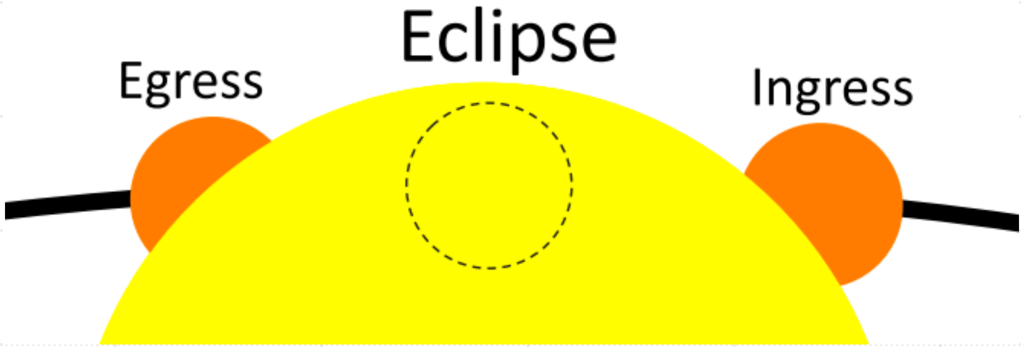
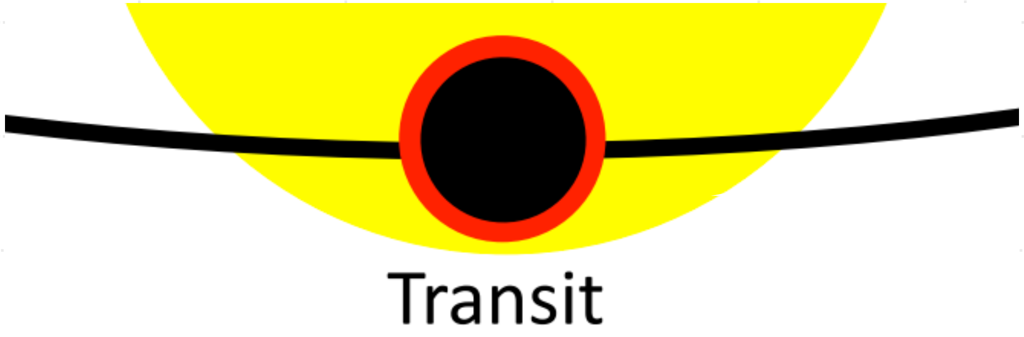


Nightside facing us

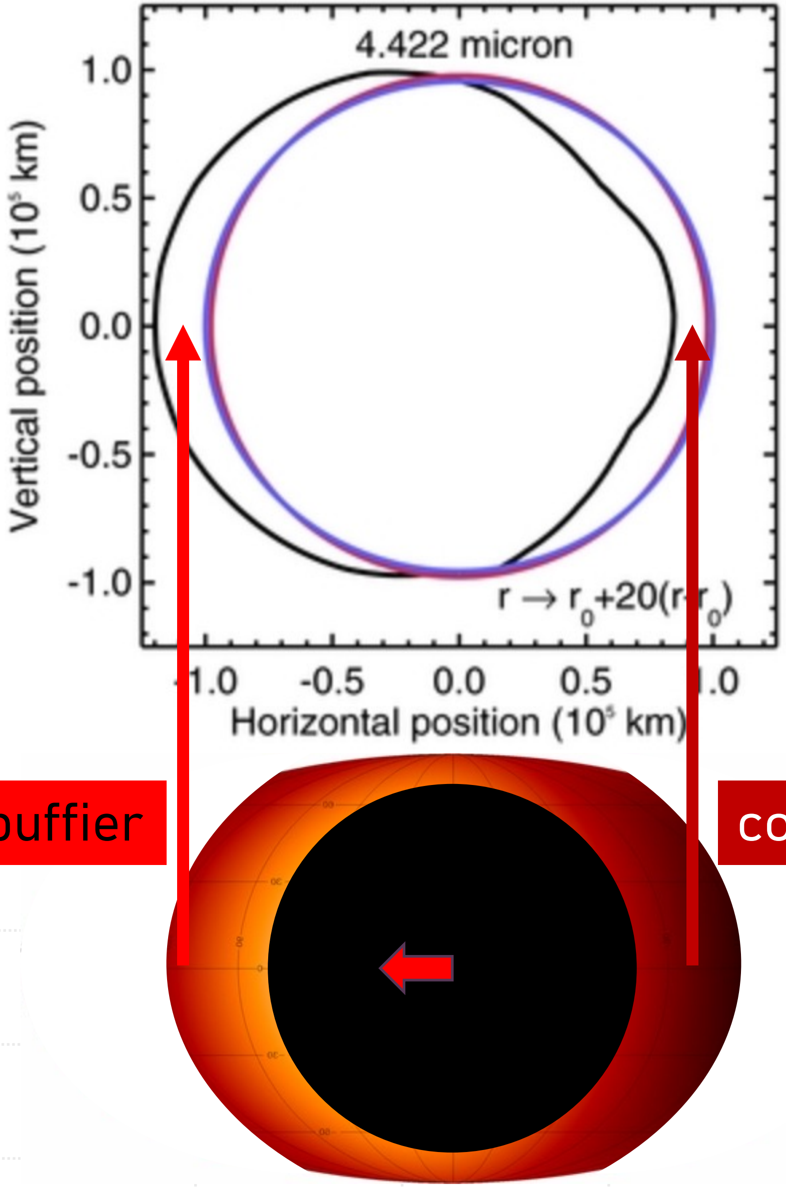






How spatial structure shows up in transit

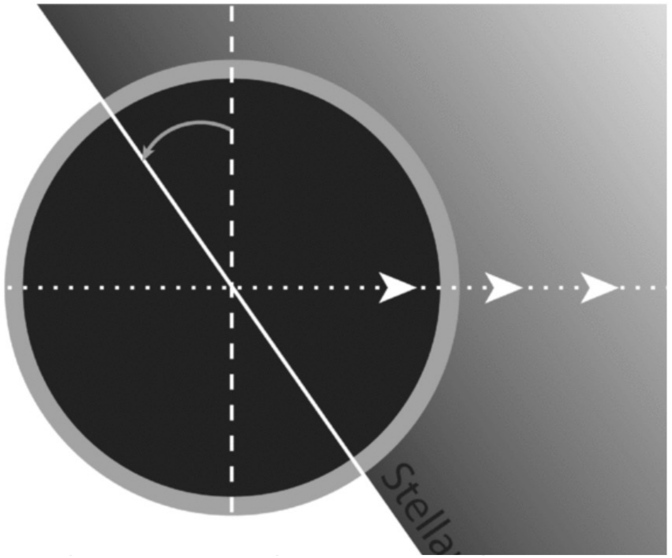
Dobbs-Dixon et al. (2012)



hotter = puffier

cooler = compact

Fortney et al. (2010)

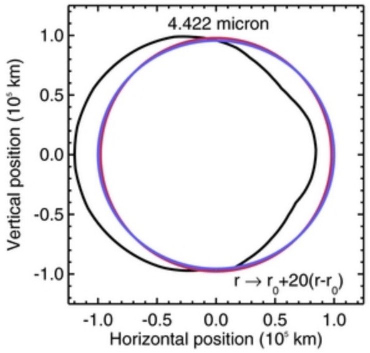


Leading and Trailing terminators

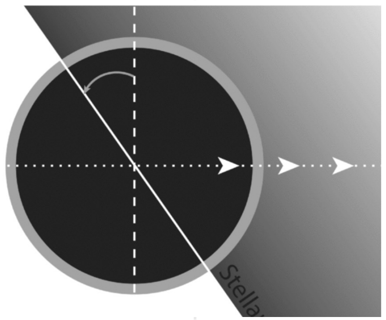
≠

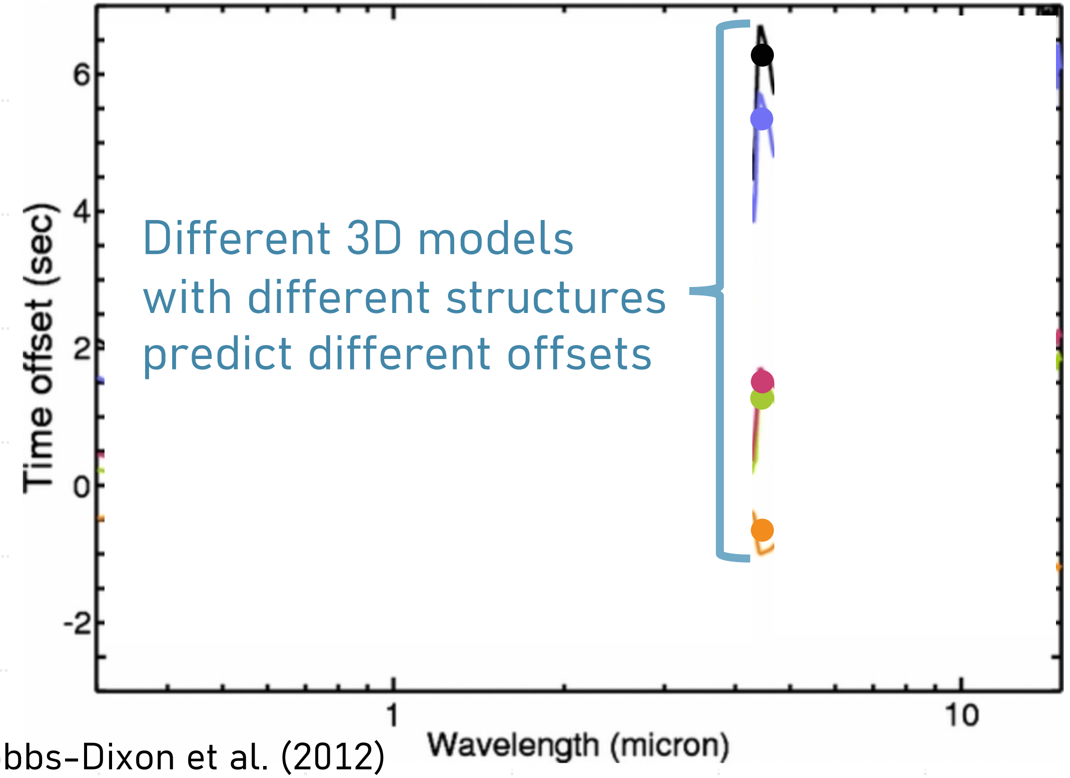
Eastern and Western terminators

How spatial structure shows up in transit



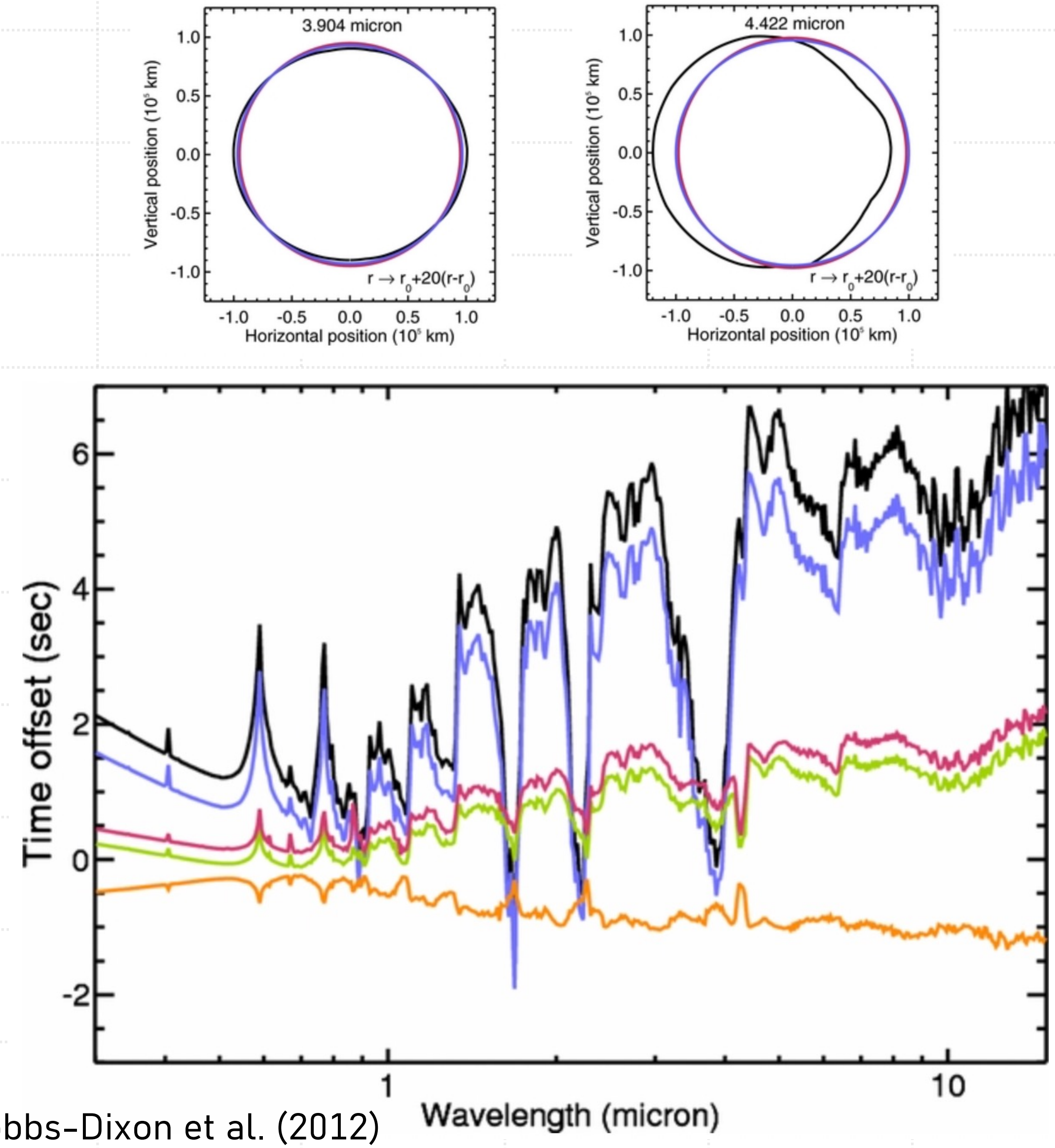
Fortney et al. (2010)





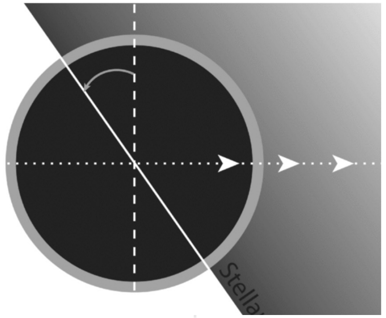
Dobbs-Dixon et al. (2012)

How spatial structure shows up in transit

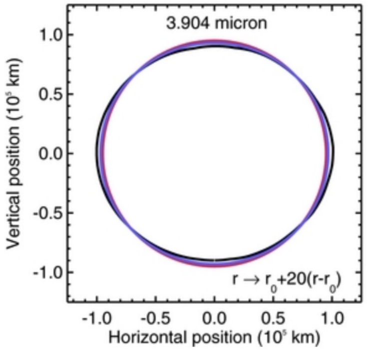


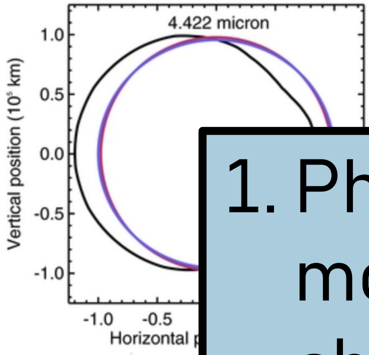
Dobbs-Dixon et al. (2012)

Fortney et al. (2010)

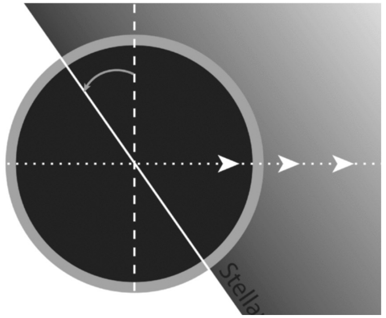


How spatial structure shows up in transit



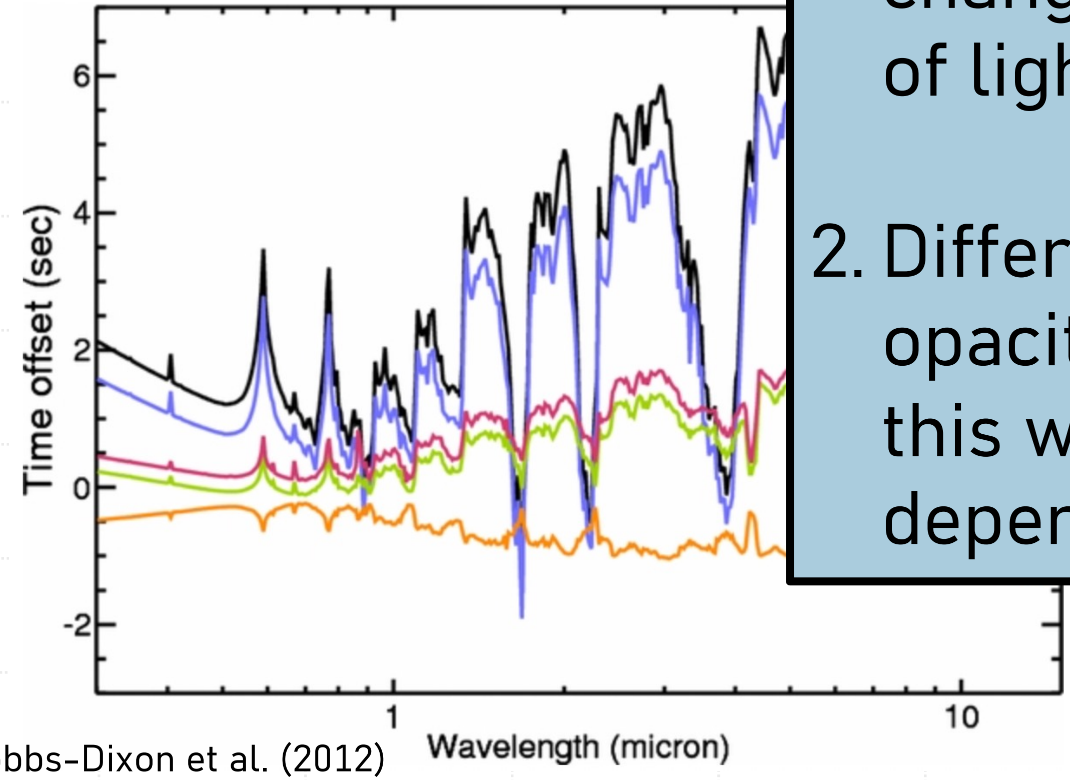


Fortney et al. (2010)

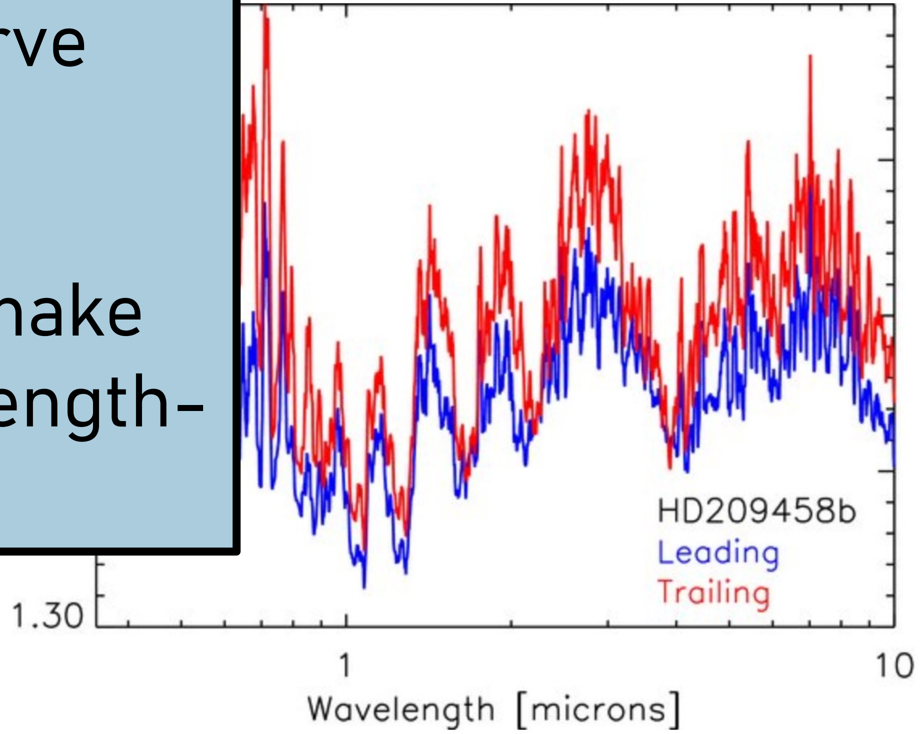


1. Physical morphology changes shape of light curve

2. Differing opacities make this wavelength-dependent

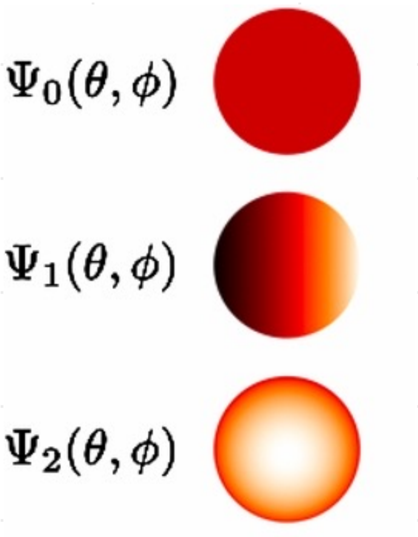


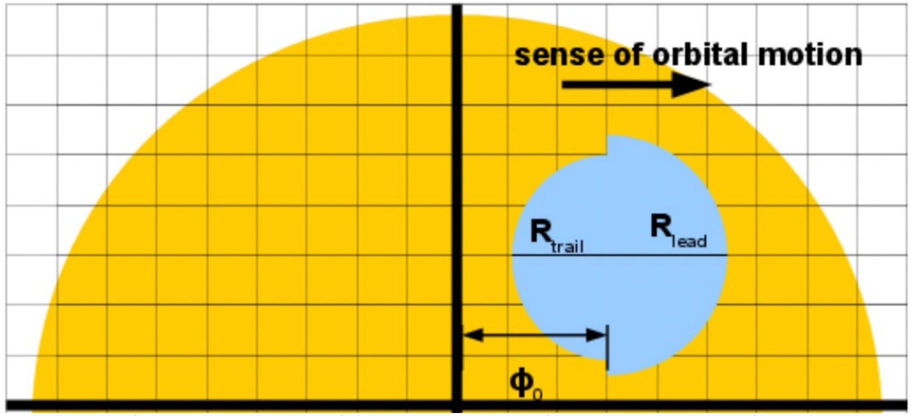
Dobbs-Dixon et al. (2012)



How do we measure 3D structure in transit?

Instead of brightness variations,
there are effective radius variations





von Paris et al. (2016)

How do we measure 3D structure in transit?

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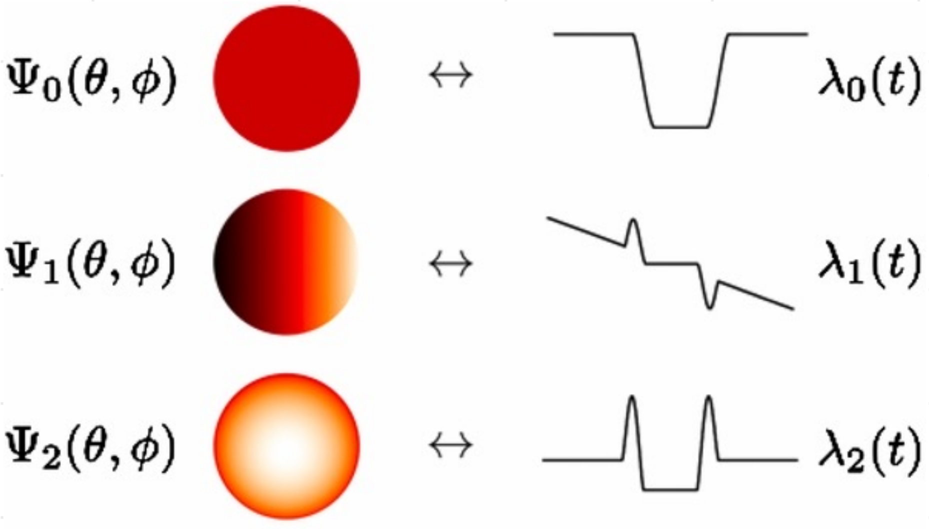
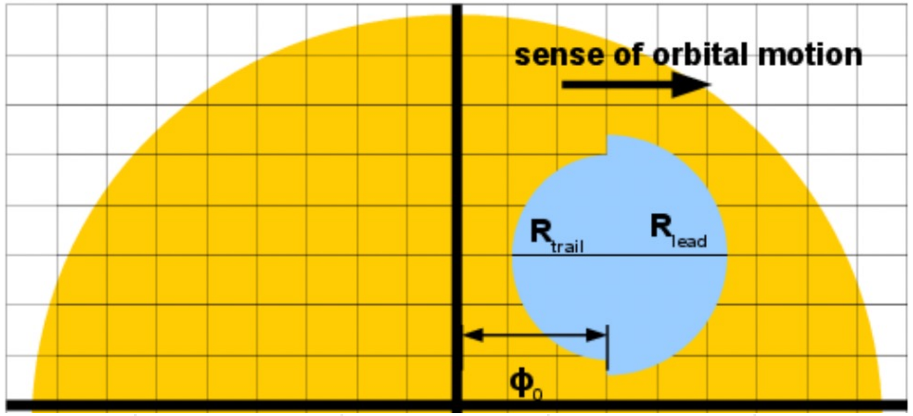
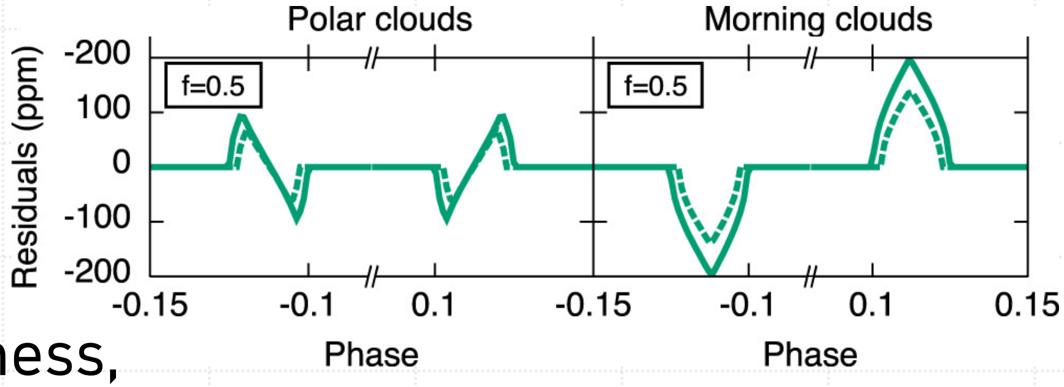




von Paris et al. (2016)

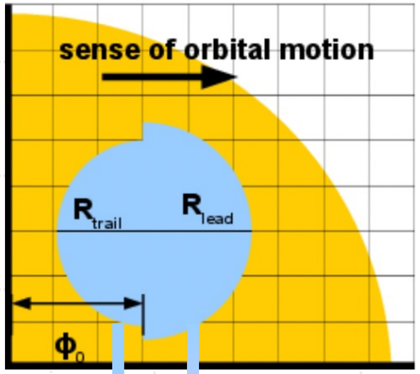


Instead of deviations from uniform brightness,
there are deviations from uniform radius

Line & Parmentier (2016)

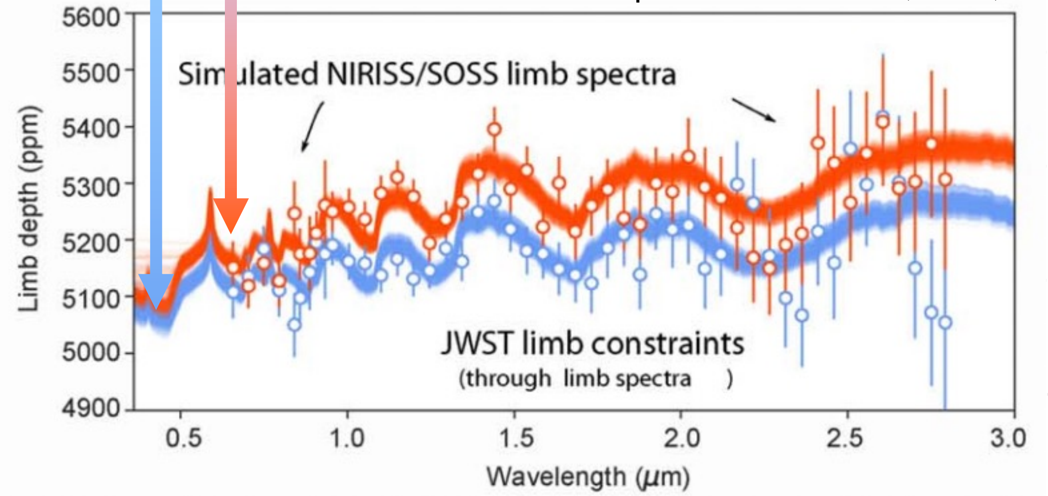
3D Transit Mapping Methods:

Model-independent

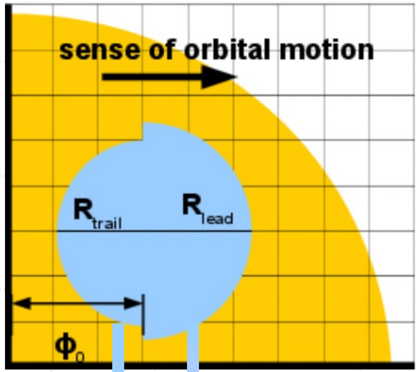


Fit $R_p(\lambda)$ for leading and trailing limbs

Espinoza & Jones (2021)



3D Transit Mapping Methods: Model-independent



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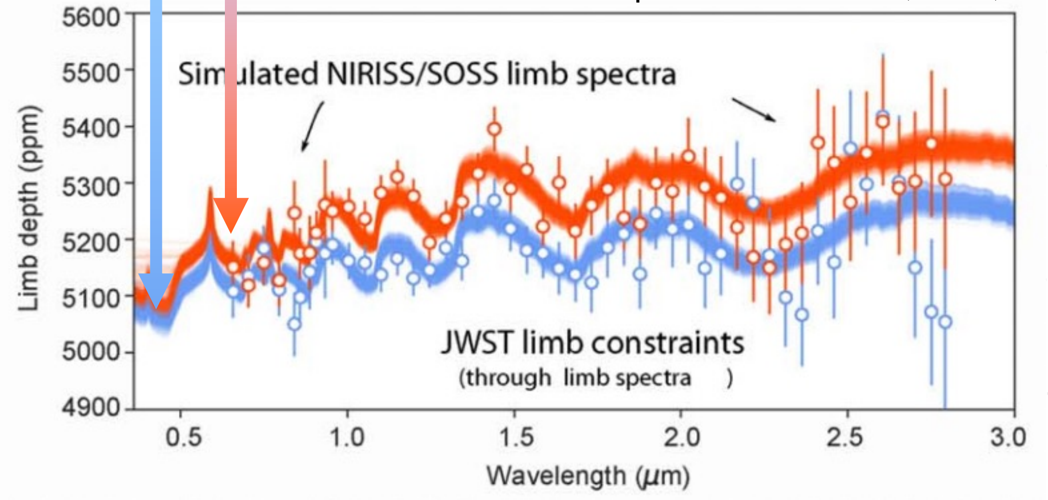
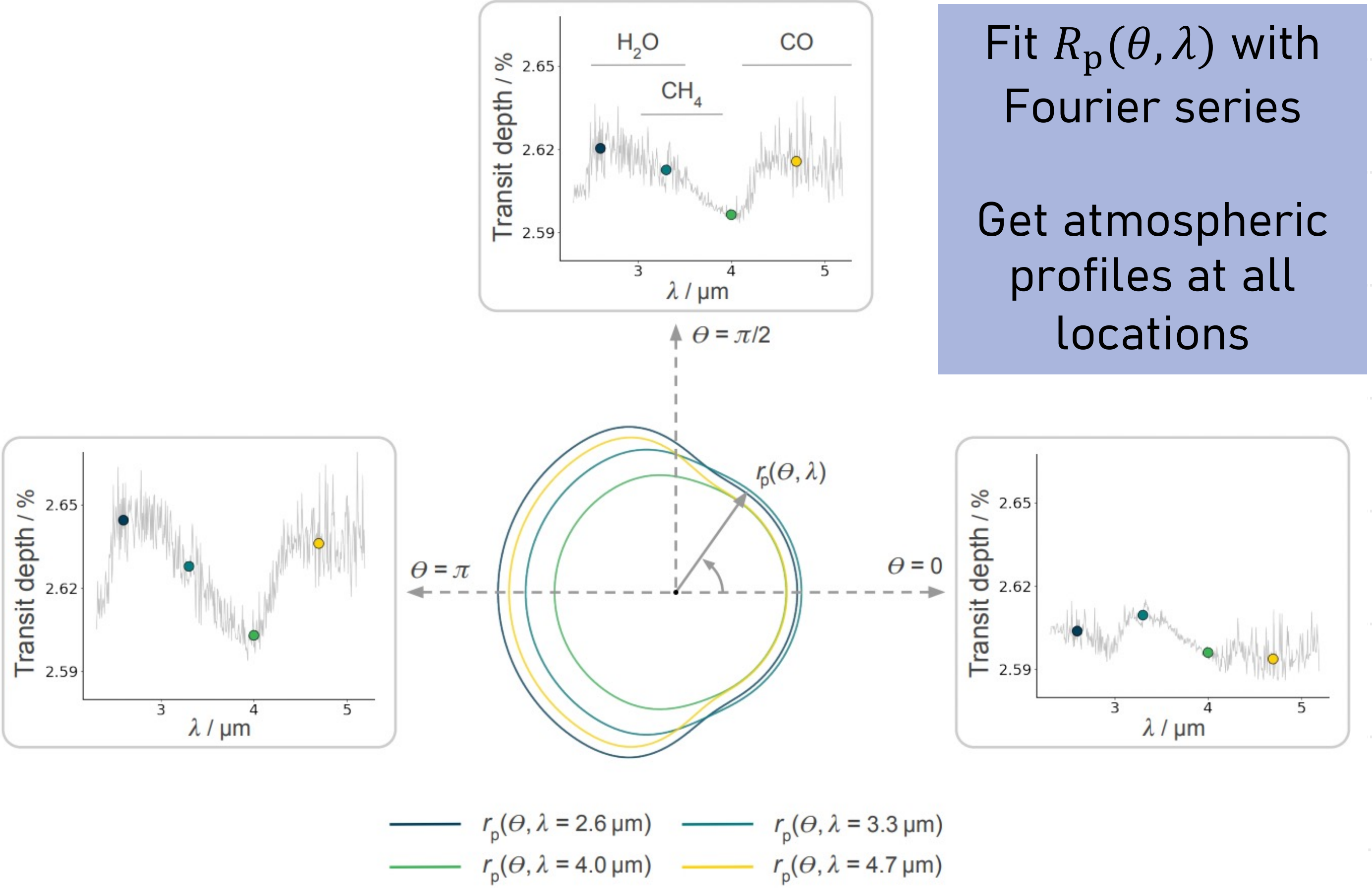
Espinoza & Jones (2021)



Fit $R_p(\theta, \lambda)$ with Fourier series

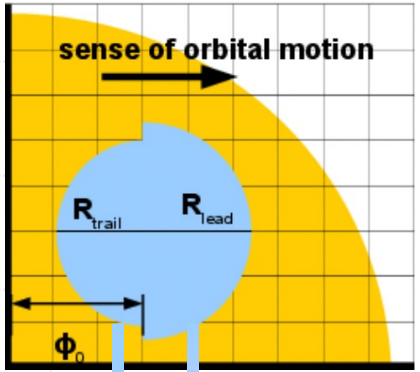
Get atmospheric profiles at all locations



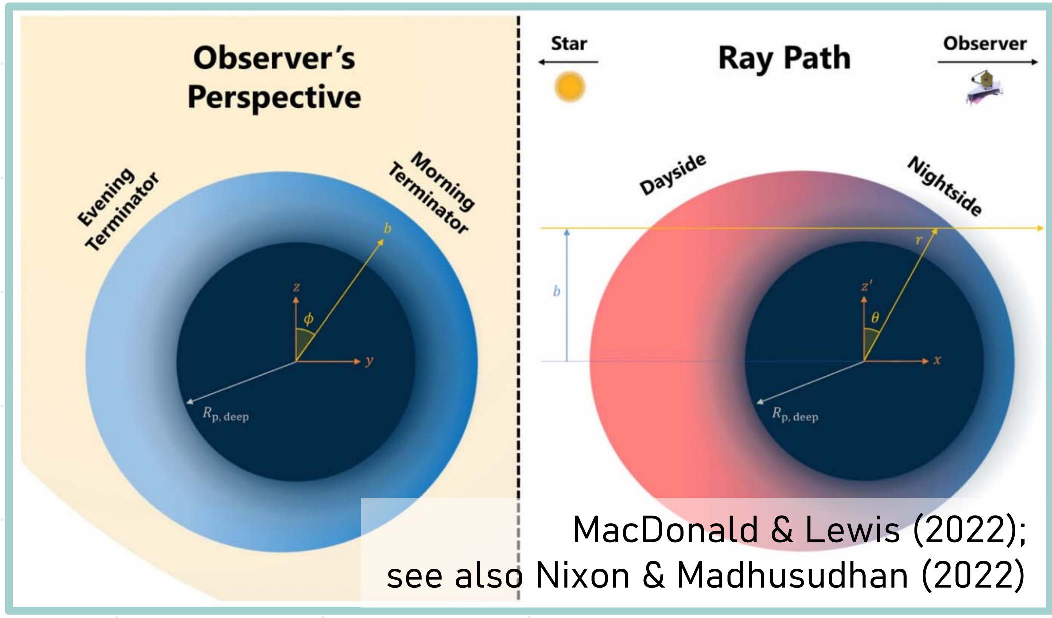
Grant & Wakeford (2022)

3D Transit Mapping Methods:

Model-independent
Parameterized structure



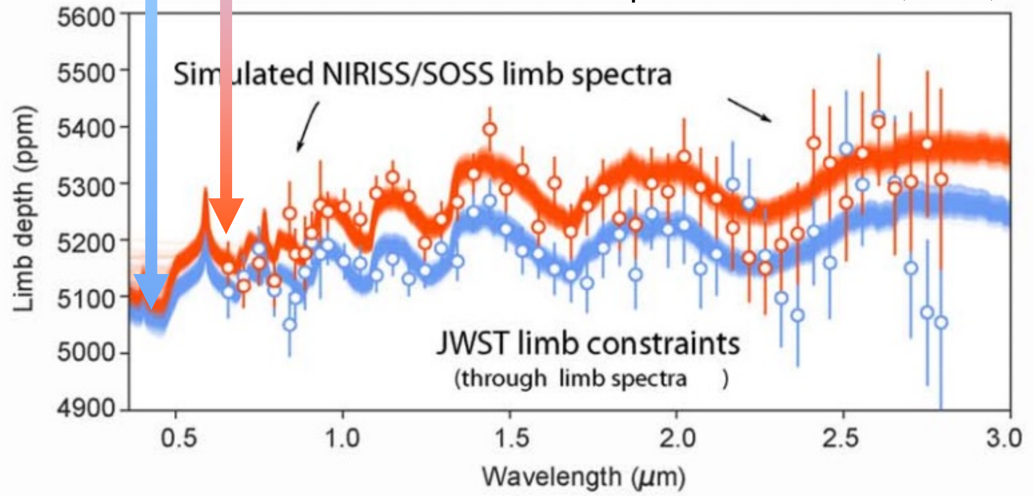
Fit $R_p(\lambda)$ for leading and trailing limbs

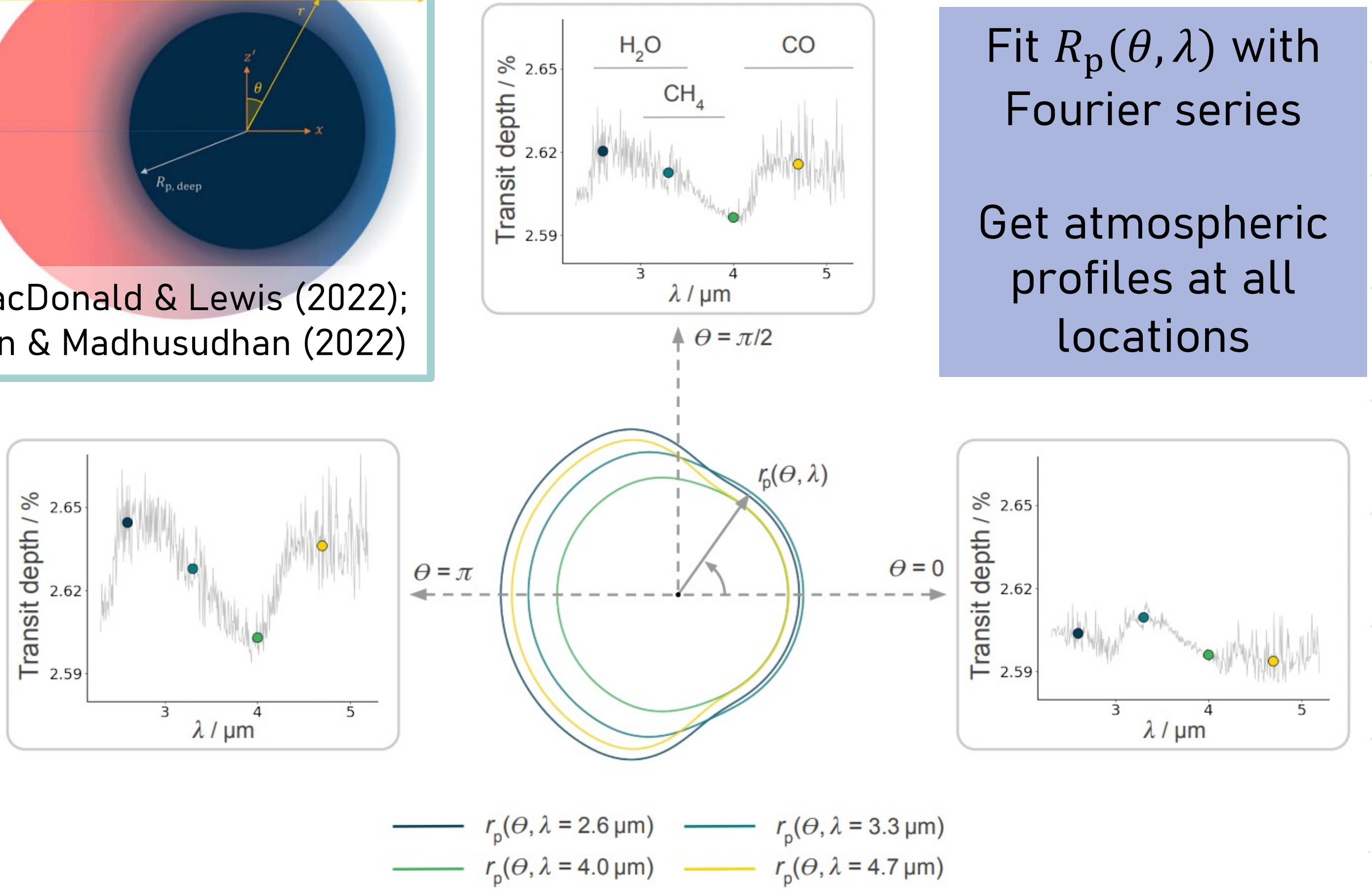


MacDonald & Lewis (2022); see also Nixon & Madhusudhan (2022)

Parameterize 3D atmospheric structure and run retrieval on spectral light curves

Espinoza & Jones (2021)



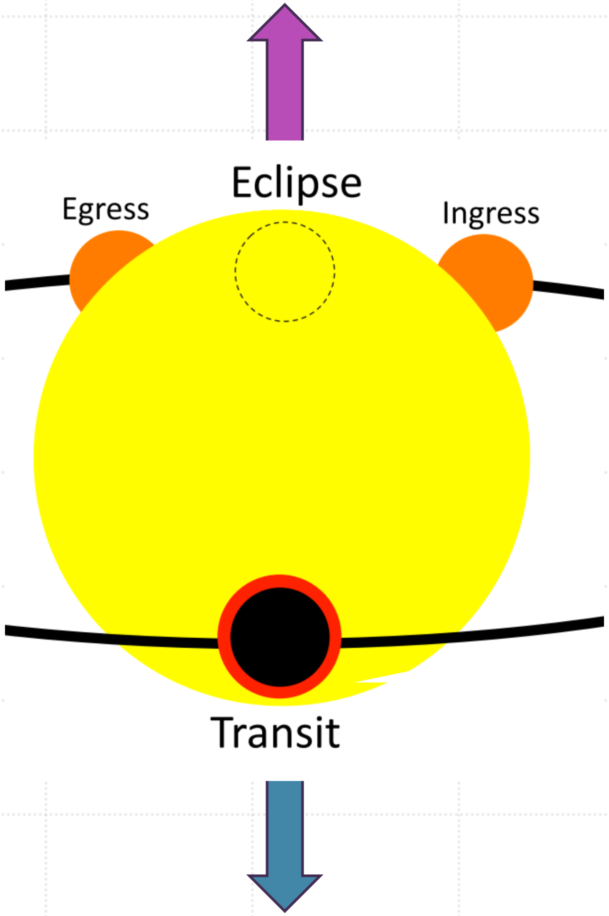


Fit $R_p(\theta, \lambda)$ with Fourier series

Get atmospheric profiles at all locations

Grant & Wakeford (2022)

Eclipse mapping
3D structure of dayside



Transit mapping
3D structure of terminator

Mapping the 3D Structure of Exoplanet Atmospheres

- How to access 3D info:
  - Latitude and longitude come from the shape of the light curve
  - Depth into the atmosphere comes from spectral differences
- Methods to extract 3D info:
  - Model-independent
  - Model-informed

With JWST we can measure atmospheres in 3D!